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OTCQB: LWLG

Global photonics markets and trends over the next decade

Michael Lebby,
CEO Lightwave Logic Inc

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Agenda

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- Key trends
- Target Markets: large & facing a growing gap
  - Market environment
  - Market gap
- Market technology opportunities
  - Faster devices, lower power, lower cost, robustness
- Roadmap update
  - What we predicted from 2016
  - What is happening in 2019
- Summary

NB: These green bars give a summary of each slide

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What does it take…

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…to enable today's data services such as streaming video, social media, activity trackers, e-commerce?

…to enable tomorrow's data services (more intelligent, more immediate, richer)?

Future products will be driven and enabled by photonics

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Actually…all this!

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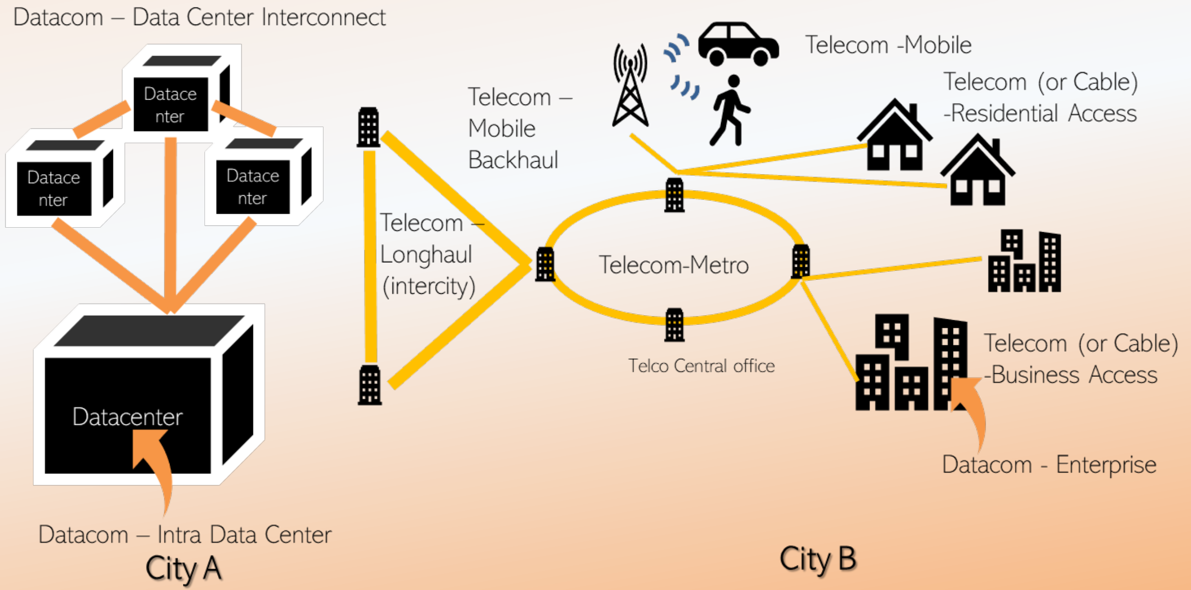
Massive datacenters and high-speed fiber optics enable today's data services such as streaming video, social media, activity trackers, e-commerce

Experts agree it will it take radical innovation to enable tomorrow's data services (more intelligent, more immediate, richer)



Radical innovation needed…

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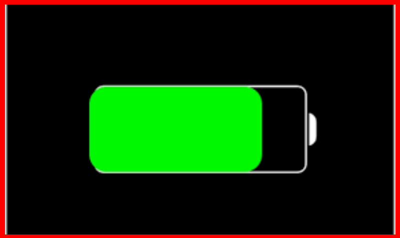
Delivering radical innovation…

Photonics must deliver solutions:

Faster devices
(100GHz+)

Lower Power
(Low voltage)



Lower cost
(Easy fab)

Robust
(Stable)

To enable faster, lower power, lower cost internet…

Source: Lightwave Logic (LWLG)

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Market Environment: Quick Review

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Value chain optical networking

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Component Suppliers

Lasers,
Modulators

High-speed Optics Manufacturers

Transceiver Modules

~$10B by 2022

Source: OIDA, Ovum

Cost of optics is growing disproportionately… this is a problem!

Networking Equipment Manufacturers

Switches & Routers

(plus lots of other equipment like servers & storage)

~$50B

Source: IDC

+ Telecom Optical Transport

~$15B

Source: OIDA, Ovum

Internet & Cloud Service Providers

Datacenters

$120B
hyperscale only,
capex spend in 2018

Source: Synergy Research

Telecom Network

$350B
Capex by 2020

Source: IHS Markit

Datacom

Telecom

Many market researchers describe big markets today

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Sample actors in the market place

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Component Suppliers

Lasers, Modulators Drivers

- FURUKAWA ELECTRIC
- LIGHTWAVE LOGIC
- MACOM — Partners from RF to Light

High-speed Optics Manufacturers

Transceiver Modules

- II-VI
- SP SOURCE PHOTONICS
- LUMENTUM
- SUMITOMO ELECTRIC — Connect with Innovation

Networking Equipment Manufacturers

Switches &

- CISCO
- NOKIA
- ciena
- HUAWEI
- ZTE

Internet & Communications Service Providers

Networks

- AT&T
- Google
- verizon
- f
- aws

All want to *understand the impact* of PICs in their network

Source: Lightwave Logic , OSFP MSA

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Summary photonics components market

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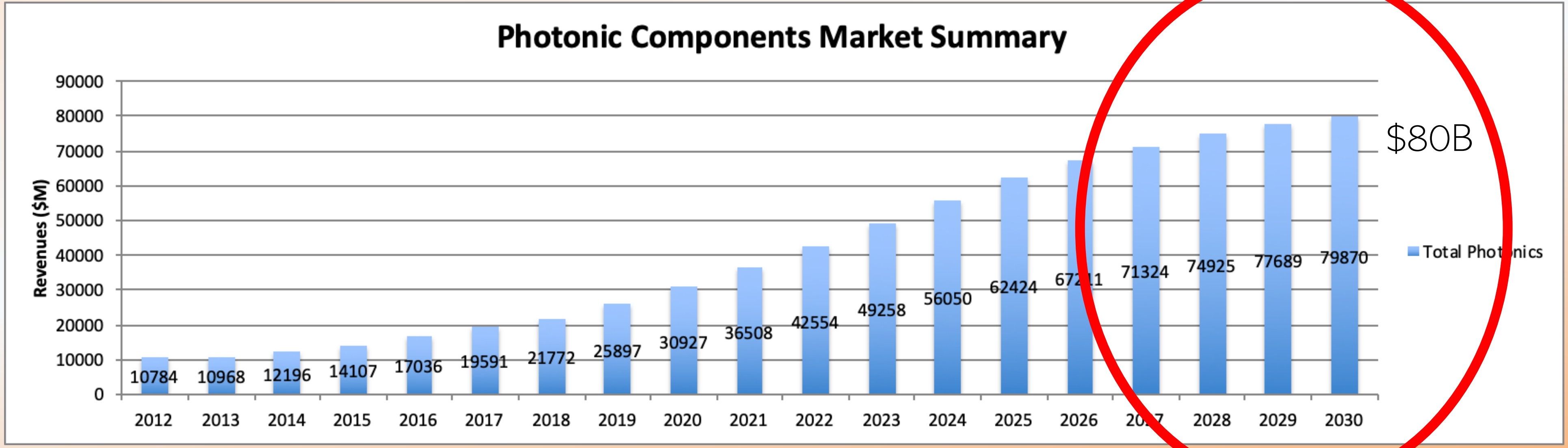
- Photonics components are forecasted to achieve $80B in 2030 with 17% CAGR (20-30)
  - Fiber optic communications



Strong growth forecasted over next decade

Source: Oculi llc

Decade perspective in photonics

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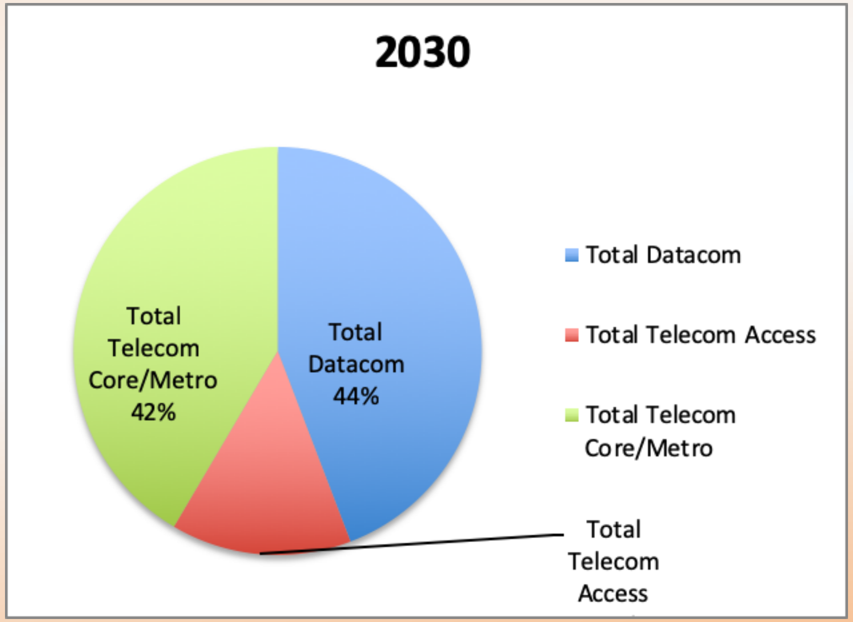
- By 2030 photonics components will be split evenly between datacom and telecom core/metro
  - Datacom $35B (22% CAGR); telecom $33B 13% CAGR)



Datacom driven by more aggressive growth

Source: Oculi llc

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Role of FO transceivers next decade

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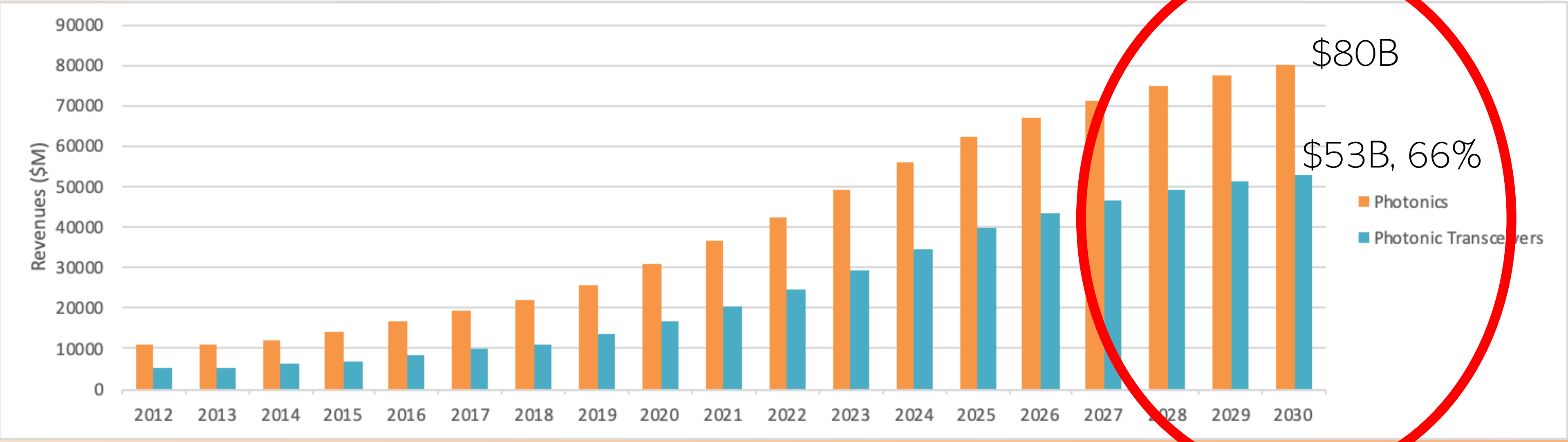
- Photonics components forecast $80B in 2030
  - 17% CAGR (20-30)
- Photonics transceivers forecast $53B in 2030
  - 21% CAGR (20-30)



Fiber optic transceiver platform continues to grow well

Source: Oculi llc

Forecast of PIC photonic components

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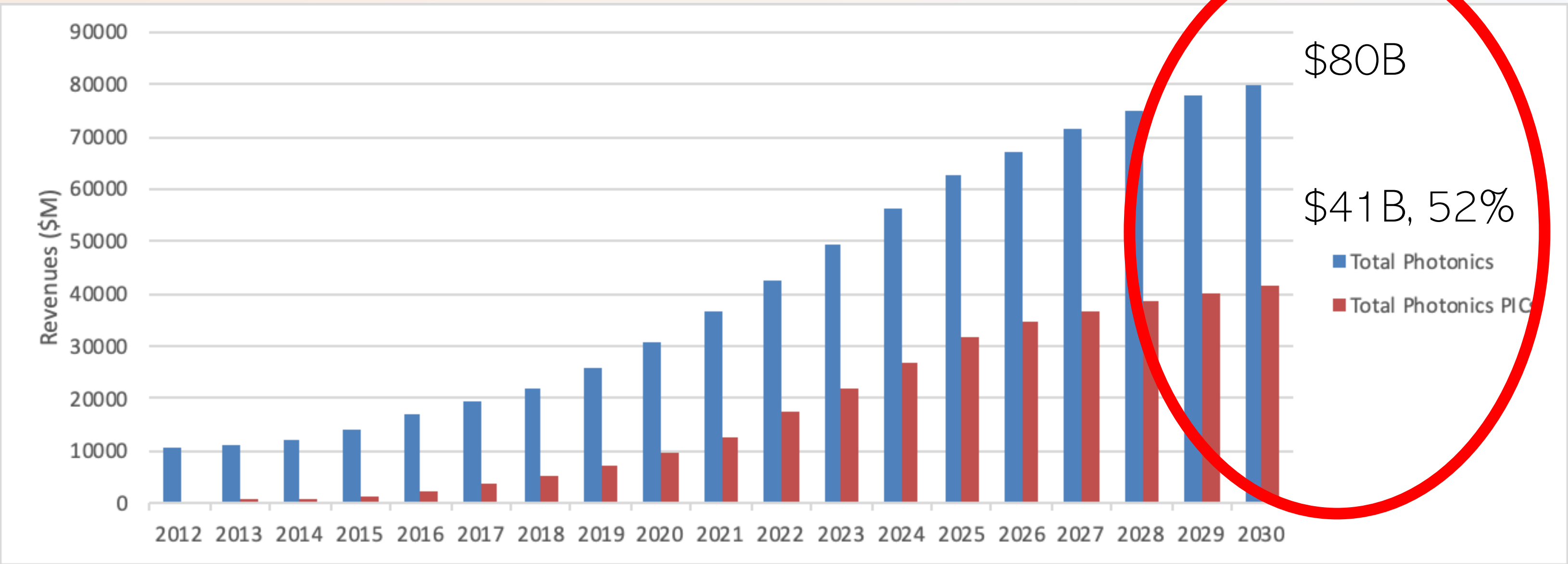
- PIC technologies ~$41B by 2030 with 29% CAGR (20-30)
  - PICs include InP, GaAs, SiP, PLC, Polymer reach 52% by 2030
  - PICs are expected to be hybrid solutions
  - PICs composed of datacom, telecom core/metro, telecom access



PIC based technologies established over next decade

Source: Oculi llc

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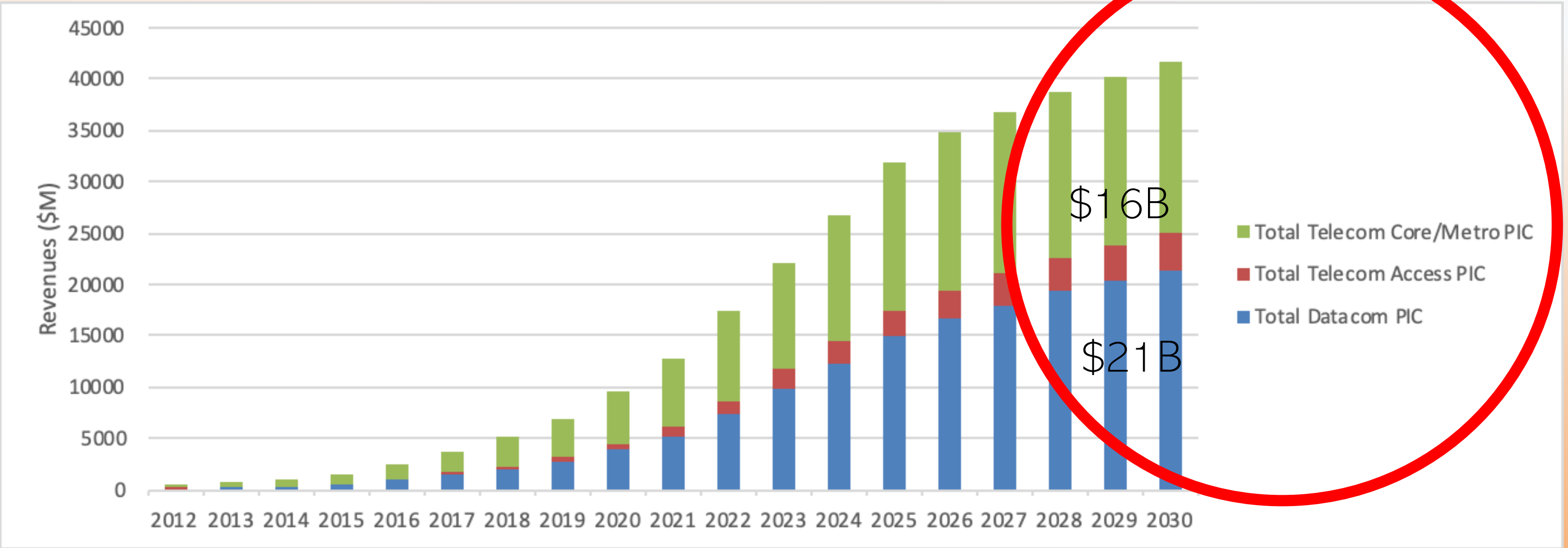
Decade forecast of PICs

- PIC technologies ~$41B by 2030
  - Datacom forecast dominant and grows to $21B by 2030 with 29% CAGR (20-30)
  - Telecom core/metro forecast slower and grows to $16B by 2030 with 28% CAGR 20-30)



PICs driven by telecom core/metro and datacom

Source: Oculi llc

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Forecast of PICs in transceivers

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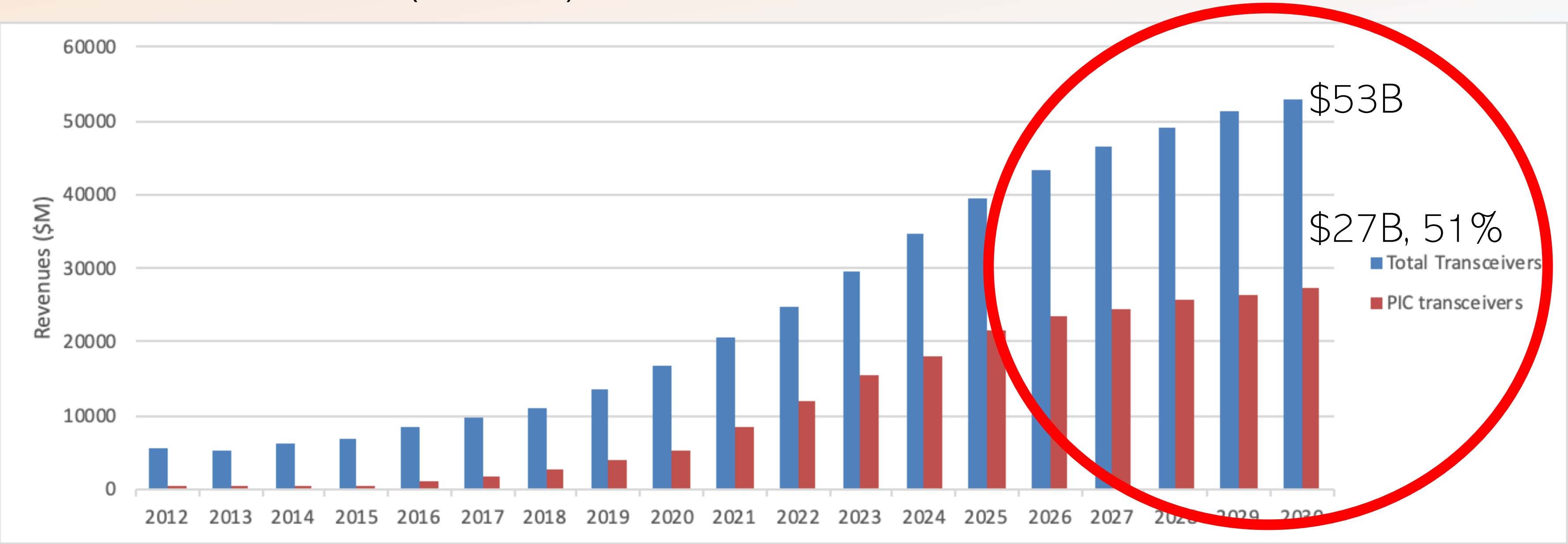
- Transceivers reach ~$53B by 2030
  - 21% CAGR (20-30)
- PIC TxRx forecasted to reach $27B by 2030
  - 31% CAGR (20-30)



PICs will become half of the transceiver mkt by 2030

Source: Oculi llc

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Forecast of Ethernet by datarate

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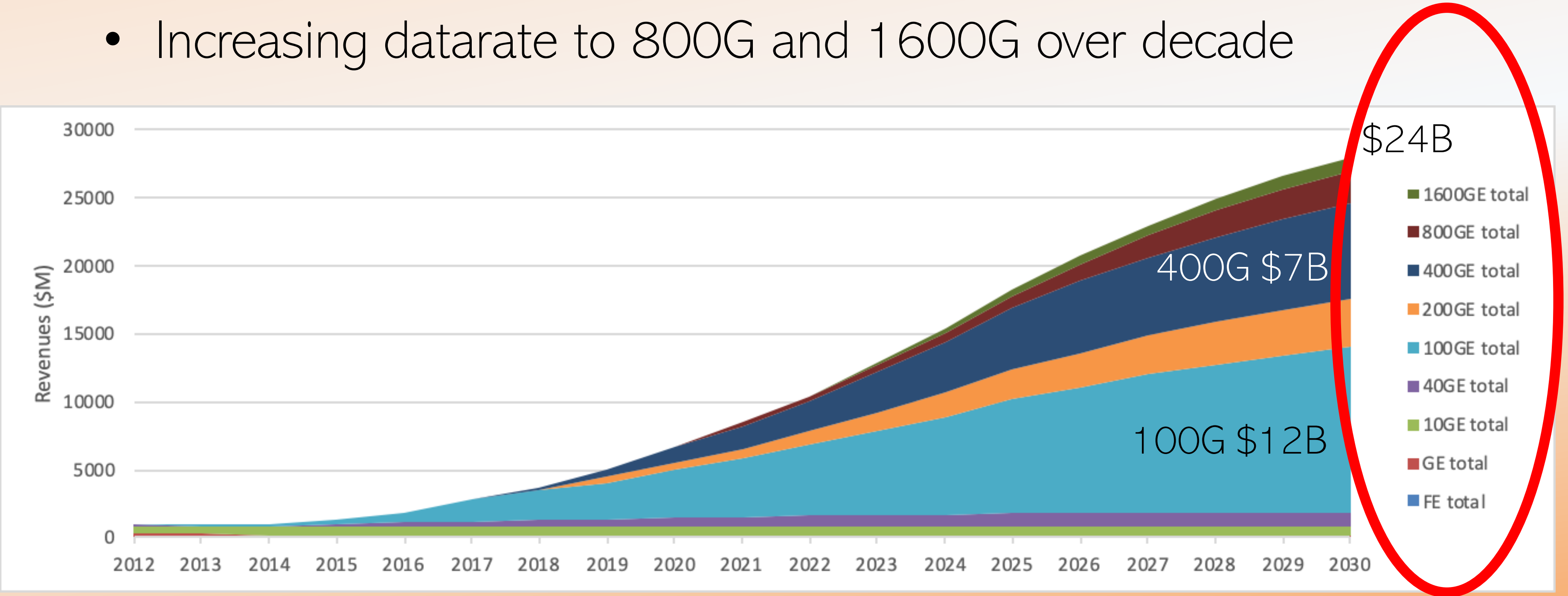
- Ethernet TxRx reach ~$28B by 2030
  - 27% CAGR (20-30)
  - Ethernet TxRx driven by 100G and 400G platforms
  - Increasing datarate to 800G and 1600G over decade



Datarate for Ethernet TxRx continues to climb to 1600Gbps

Source: Oculi llc

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Forecast of DWDM TxRx by datarate

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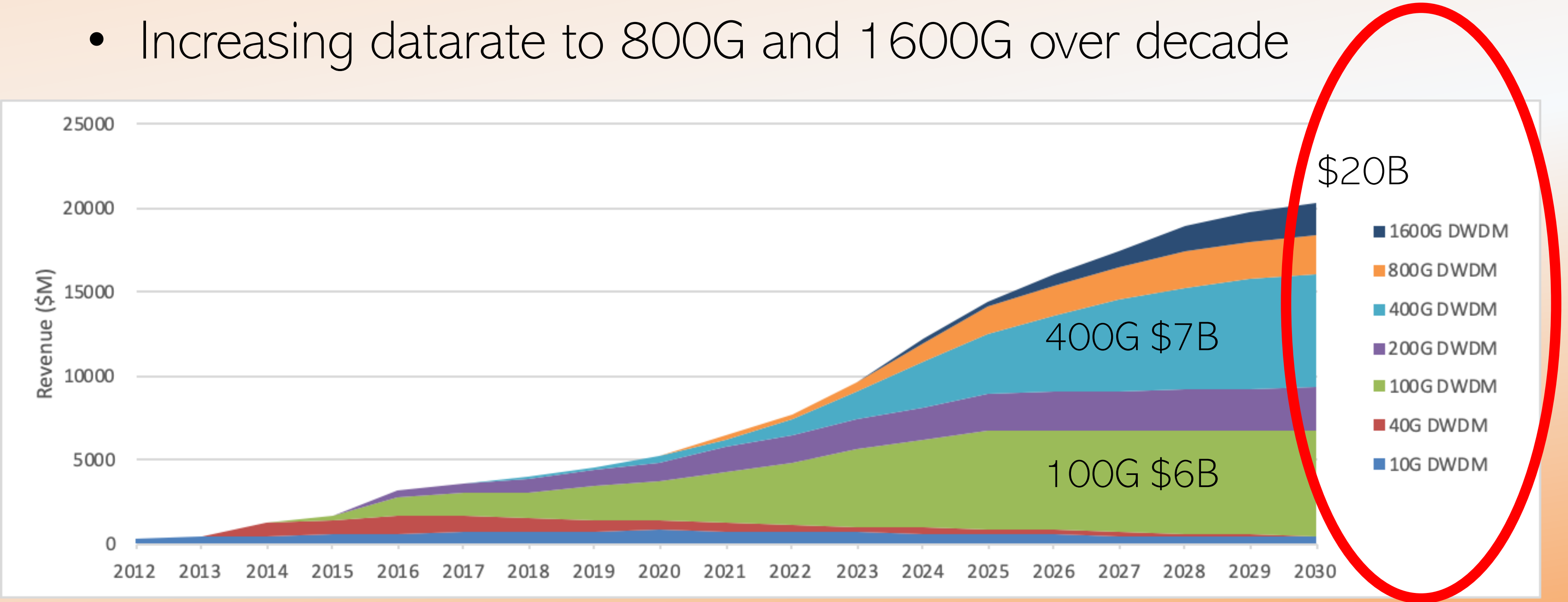
- DWDM TxRx reach ~$20B by 2030
  - 27% CAGR (20-30)
  - DWDM TxRx driven by 100G and 400G platforms
  - Increasing datarate to 800G and 1600G over decade



Datarate for DWDM TxRx also climbs to 1600Gbps

Source: Oculi llc

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Important PIC metrics…

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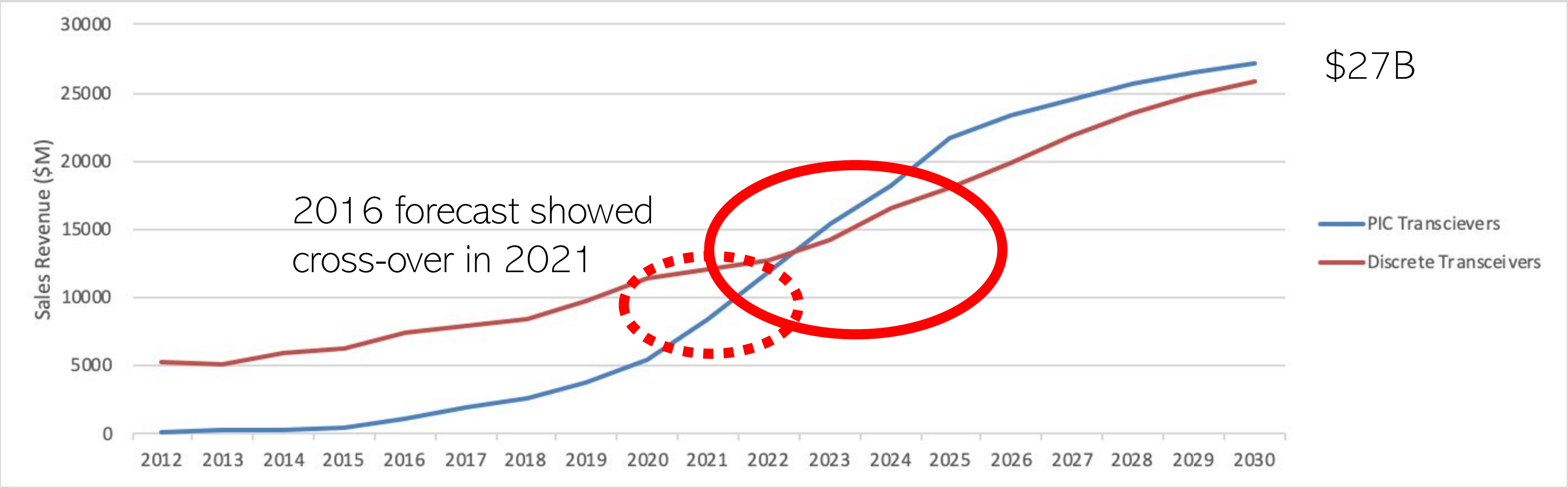
- PIC TxRx forecast against discrete TxRx to 2030
  - PIC based TxRx are expected to reach $27B in 2030
  - PIC based technologies lead the segment by end of decade



Slower pick-up of PIC transceivers in 2019 forecast

Source: Oculi llc

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Market Environment: Growing gap

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Everyone knows this…

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IP traffic

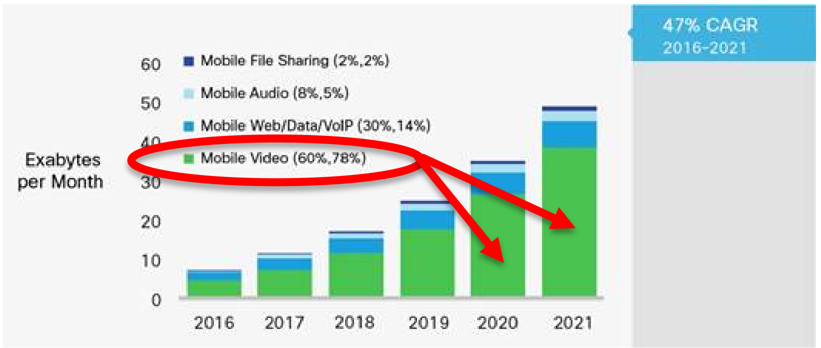
Traffic per End User

Old phone Kbps → *Kilo* = 10^3

Old "broadband" Mbps → *Mega* = 10^6

New home Gigabit broadband → *Giga* = 10^9

X More End Users



Traffic yesterday → *Peta* = 10^{15}

Traffic today → *Exa* = 10^{18}

Traffic tomorrow → *Zetta* = 10^{21}

Coming soon → *Yotta* = 10^{24}

Total Internet Traffic

Video has driven massive growth, and continues to increase

Source: Cisco VNI

Market gap in the network is a challenge

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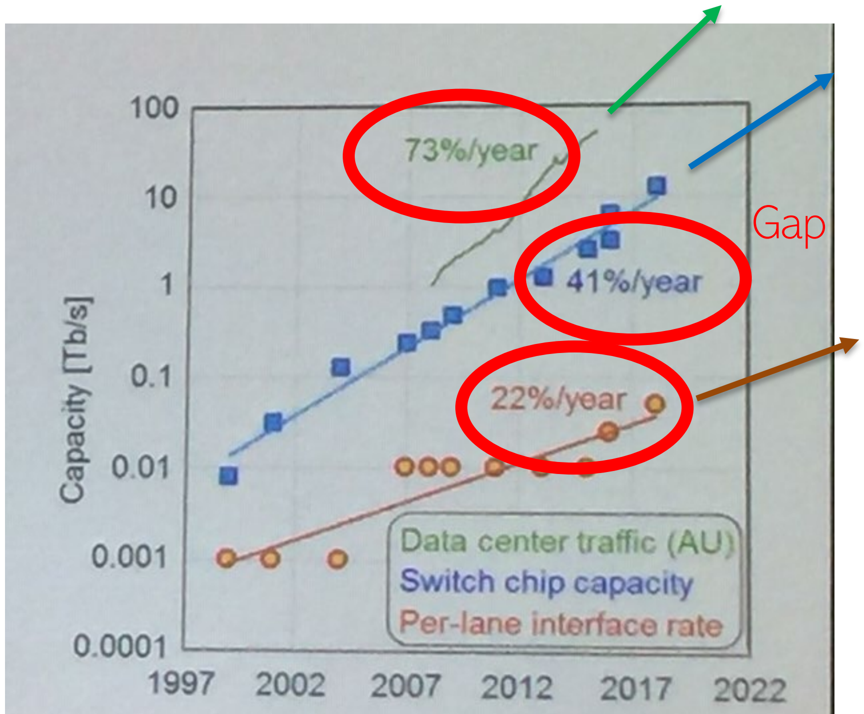
- Network speeds lagging
  - Growing at only half the rate as computing and switching electronics
  - Gap has been growing for decades!
- Now the network is starting to limit cost, power and scalability of datacenters
- <u>Business as usual is not going to keep services and the internet growing</u>



Source: Lightwave Logic (LWLG), ON2020 IEEE

Theme – we will need to *radically innovate* to reduce the gap…

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Market technology opportunities

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Faster devices…

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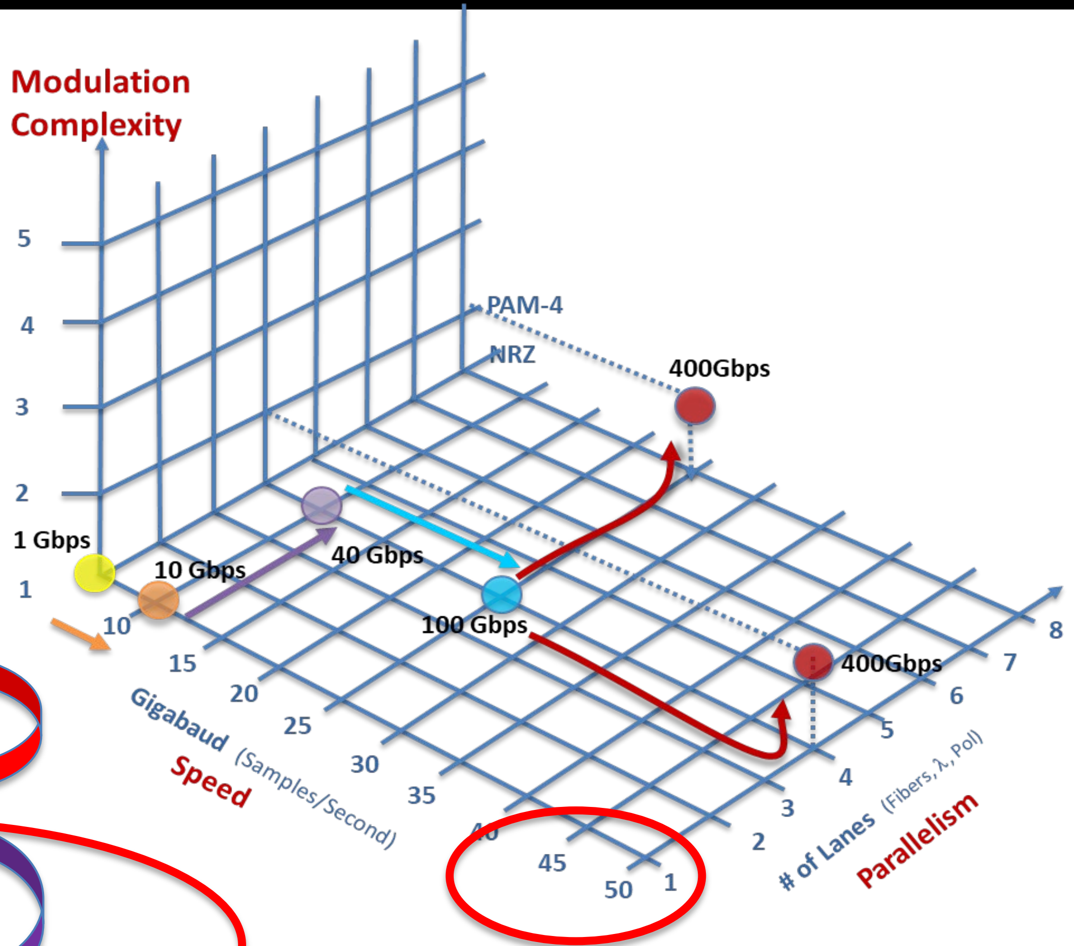
But the internet has been growing fine, so what's changed?

Historical perspective

- 1Gbps: 1 lane x 1Gbps (1990s)
  Easy
- 10Gbps: 1 lane x 10Gbps (circa 1999-2000)
  Tougher
- 40Gbps: 4 lane x 10Gbps (early 2000s)
  Tougher
- 100Gbps: 4 lane x 25Gbps (early 2010s)
  Difficult
- 400Gbps: 4 lane x 50Gbps PAM4
  400Gbps: 8 lane x 25Gbps PAM4
  (2015 onwards)
  Much more difficult
  800Gbps
  1600Gbps



Things get tougher with increasing data rates

Source: Lightwave Logic

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Traffic capacity: road analogy

Good roads: Faster cars: more traffic capacity

More lanes: more traffic capacity

Already did the easy things like paving the road and adding more lanes

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Traffic handling: road analogy

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Industry has already done the harder stuff like ‘higher order modulation’

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What about speed?

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Still ~60 mph

10 mph → 60 mph

Speed has hit a plateau…

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Speed limited by conventional photonics

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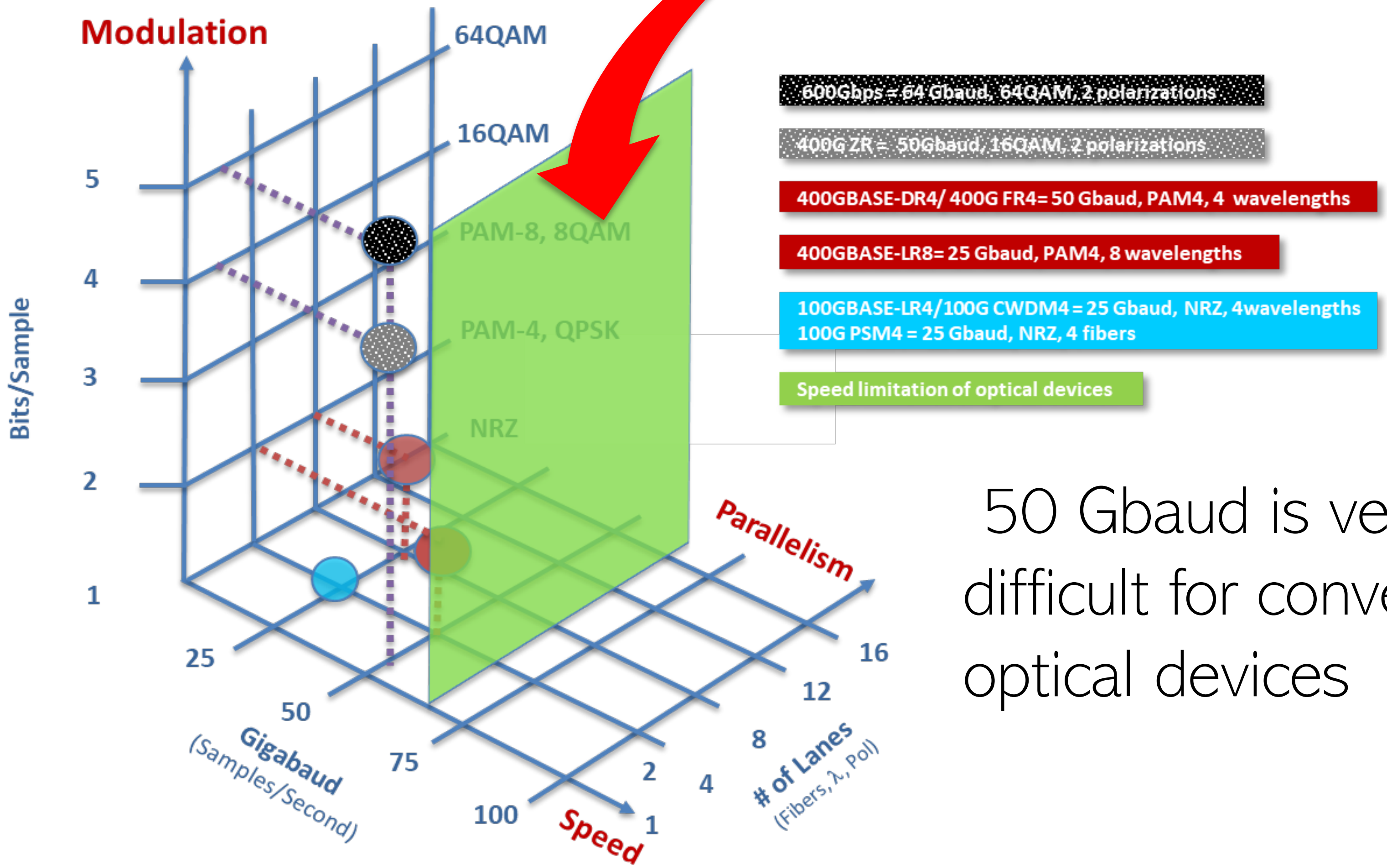

50 Gbaud is very difficult for conventional optical devices

Speed limited by device physics

Plastic polymers break the speed limit…

Polymers are faster than other technologies

Polymers double the native data traffic to 100Gbps (before counting multiple lanes, stacking…)

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Innovation to break the speed barrier

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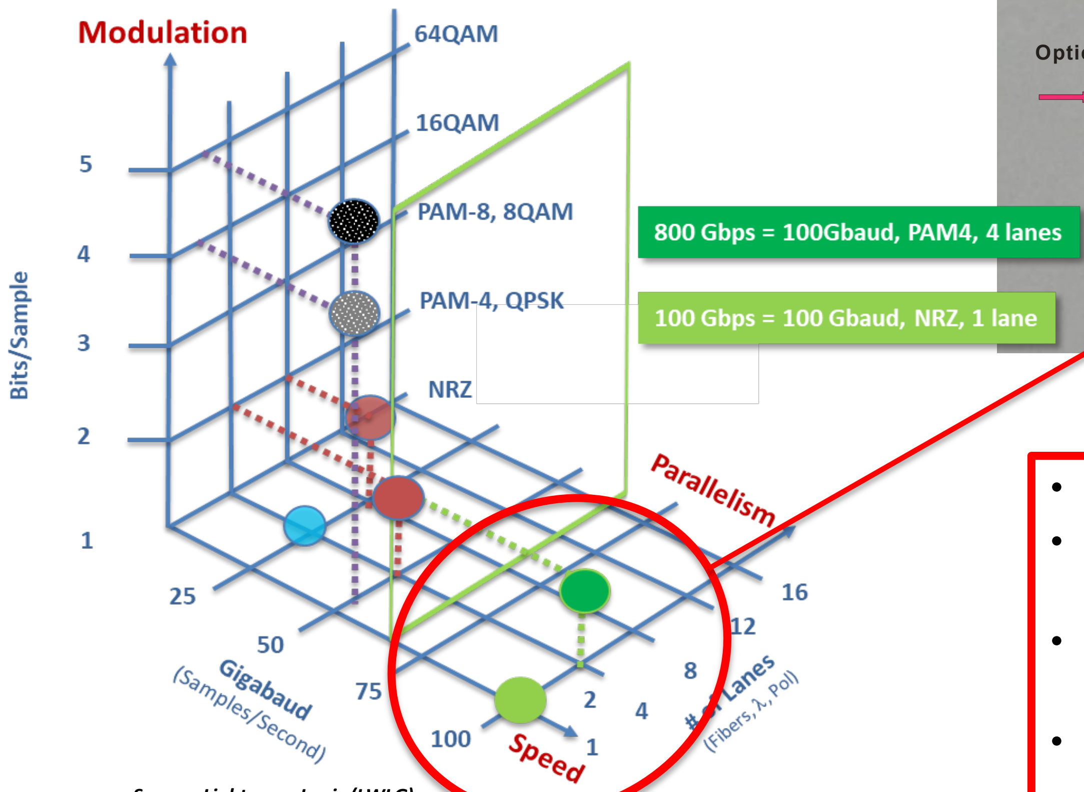
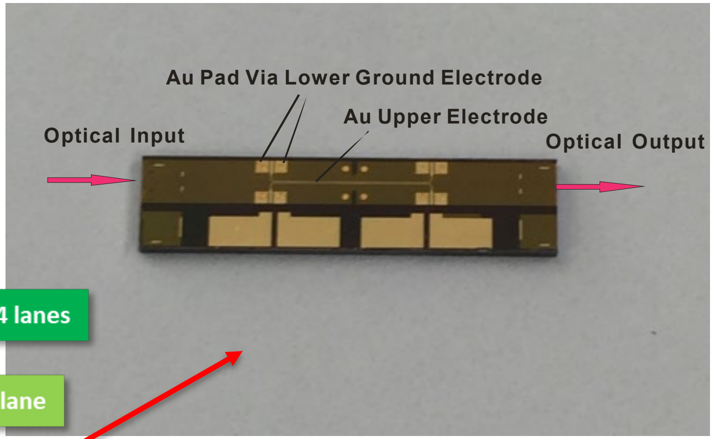


Source: Lightwave Logic (LWLG)



- *Options can be:*
- 100G, 1V
  - 100Gbaud, NRZ, OOK
- 400G, 1V
  - 4 Channel x 100G NRZ, OOK
- 800G, 1V
  - 4 Channel x 100G, PAM-4

Renewed ability to grow traffic capacity

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Lower power

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Everyone knows this too…

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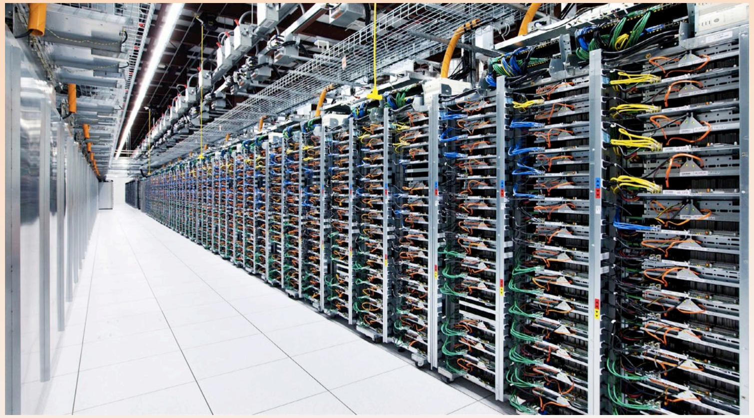
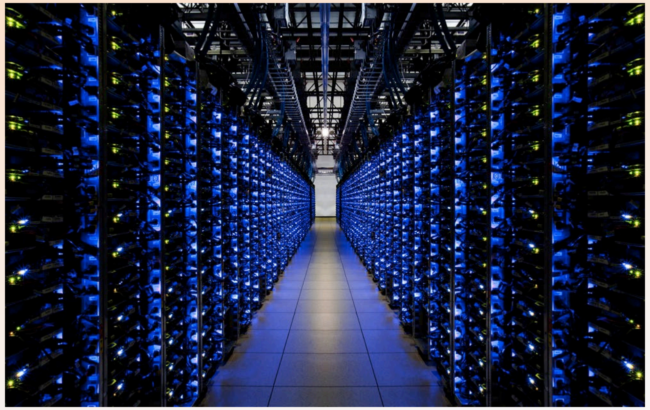
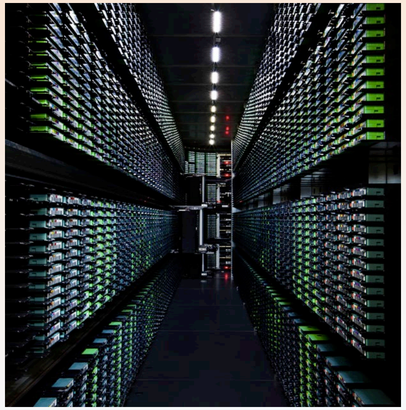


Power is limiting datacenter growth

Source: Google

Drive to greater density

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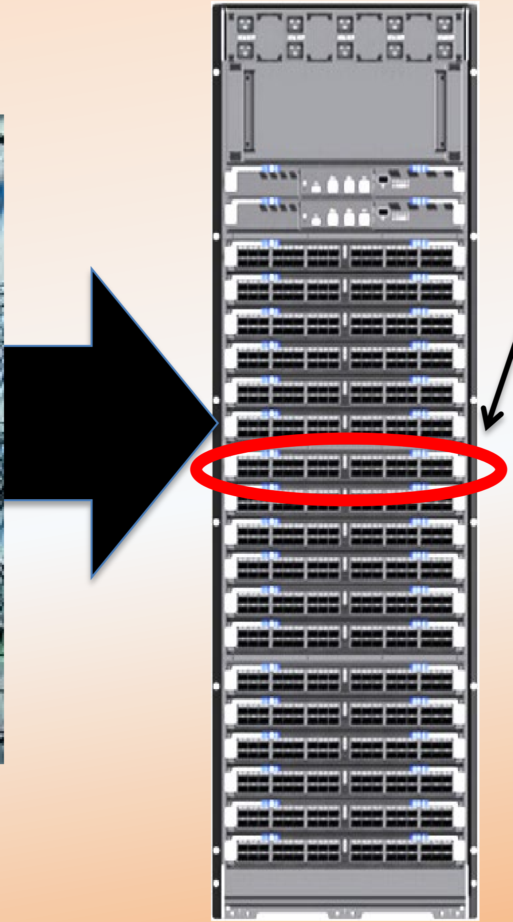

Equipment capacity is limited by how many transceivers can fit on the faceplate

Faceplates are where traffic enters and exits in the datacenter

Source: Facebook

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Denser faceplates means smaller optics

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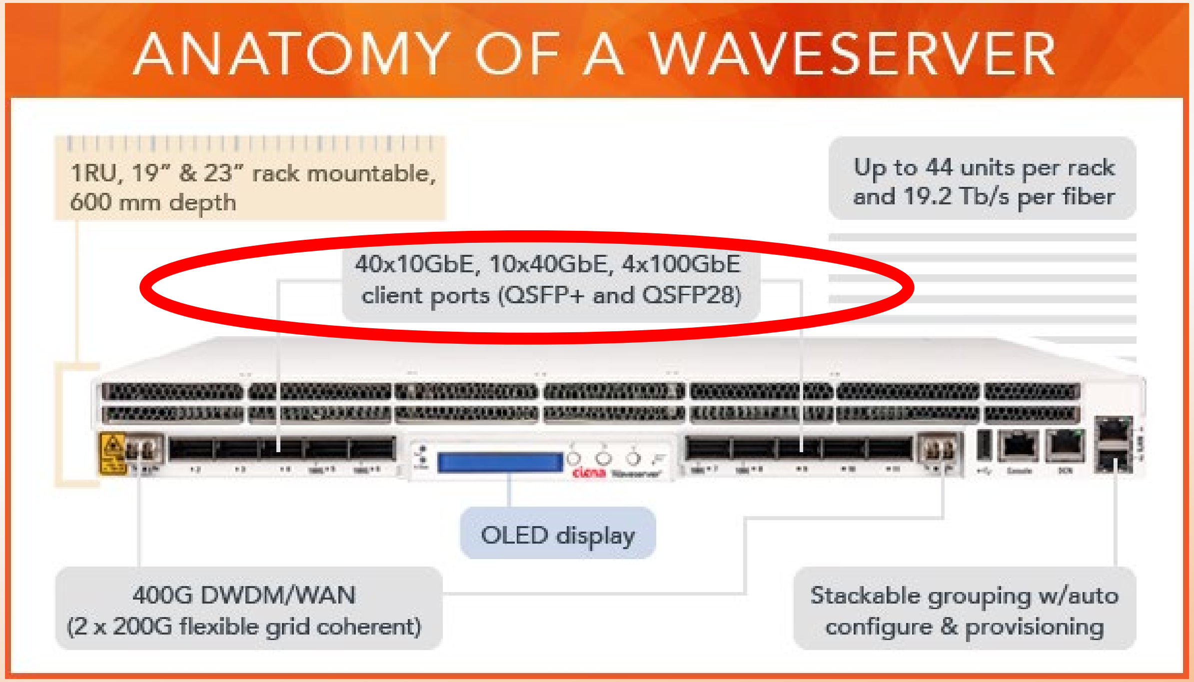
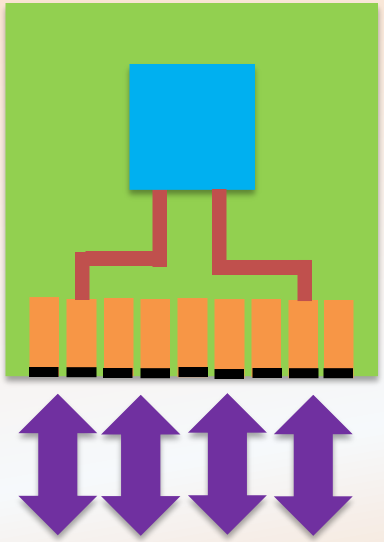
- Customers are requesting 50-100 Tbps solutions
- This faceplate is only 1.2 Tbps!





Top View

Incremental improvements won't give the *100x increase*

Source: Ciena

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Are pluggables reaching a limit?

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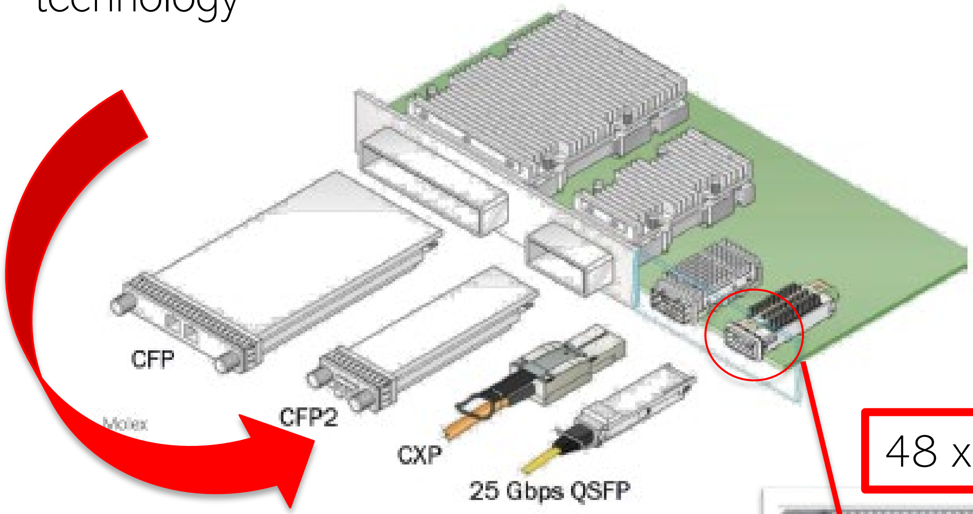
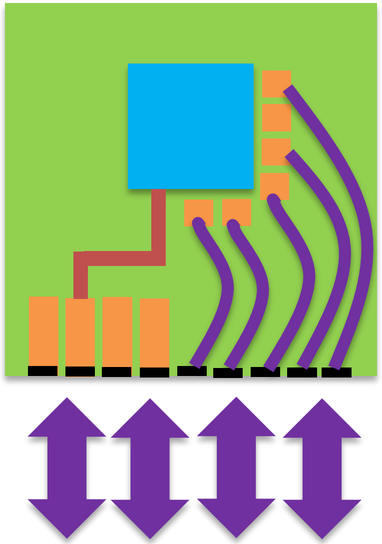
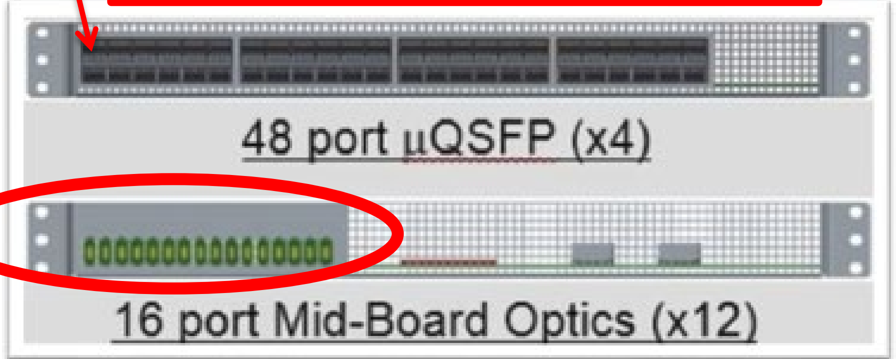
Transceiver boxes have been shrinking quickly… which *opens opportunities* for polymer based technology





Top View

48 x uQSFP (100G) = 4.8Tbps



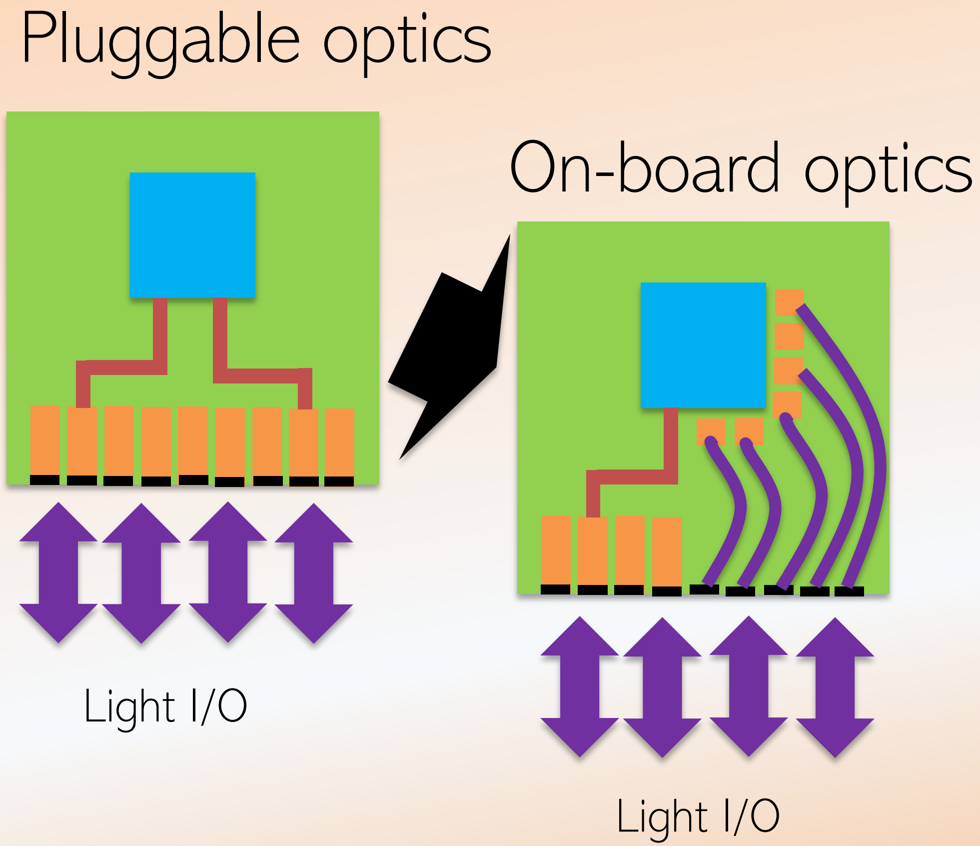
Standard 1RU faceplate with 48 ports

By using 16 fibers to connect TxRx on board then more room on faceplate for cooling

Combination – fiber on-board optics and pluggable?

Source: TE Connectivity, Molex

Trend today: pluggable → on-board



- Pluggable optics
  - Limit in physical size of pluggable boxes
- On-board optics
  - Stepping stone to bringing optics closer to the switch electronics

Will these solutions suffice for 100Tbps+ ?

Source: Lightwave Logic (LWLG), OFC2019

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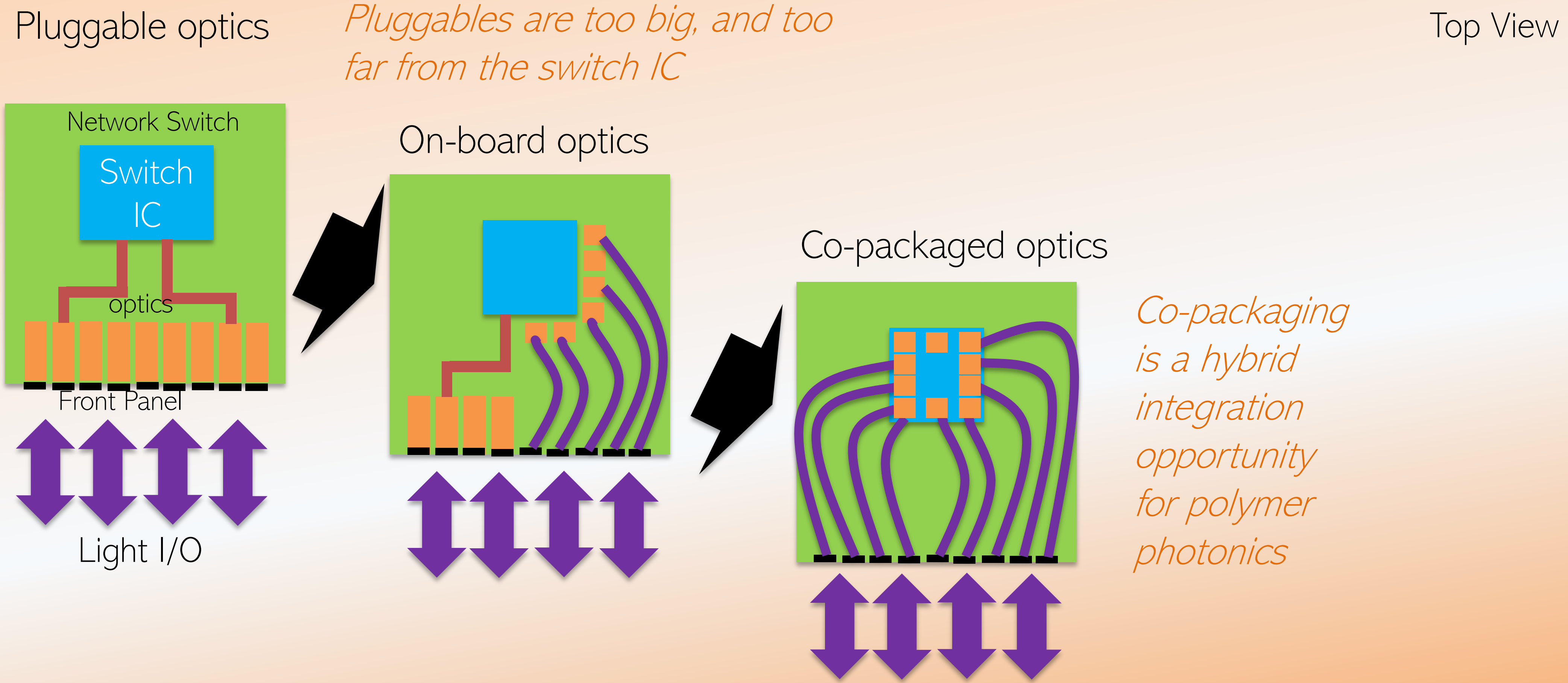
Co-package the optics...

Pluggables are too big, and too far from the switch IC



Co-packaging is a hybrid integration opportunity for polymer photonics

Trend: move from TxRx to multi-chip modules (MCM) like electronics did 25 Yrs ago

Source: Lightwave Logic (LWLG), OFC2019

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Co-packaging – full integration

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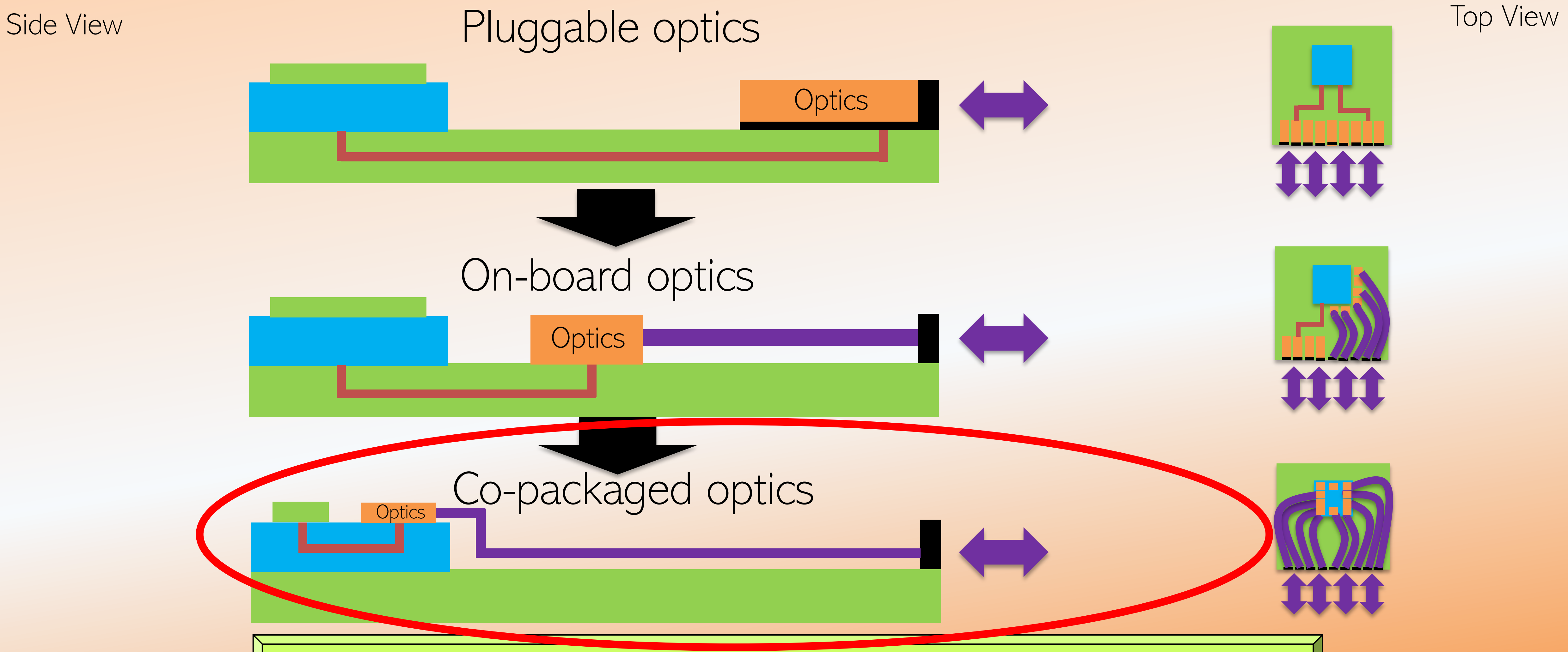

True photonic integration – Board scale PIC technology

Source: Lightwave Logic (LWLG),

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Scaling the co-packaged PIC engine

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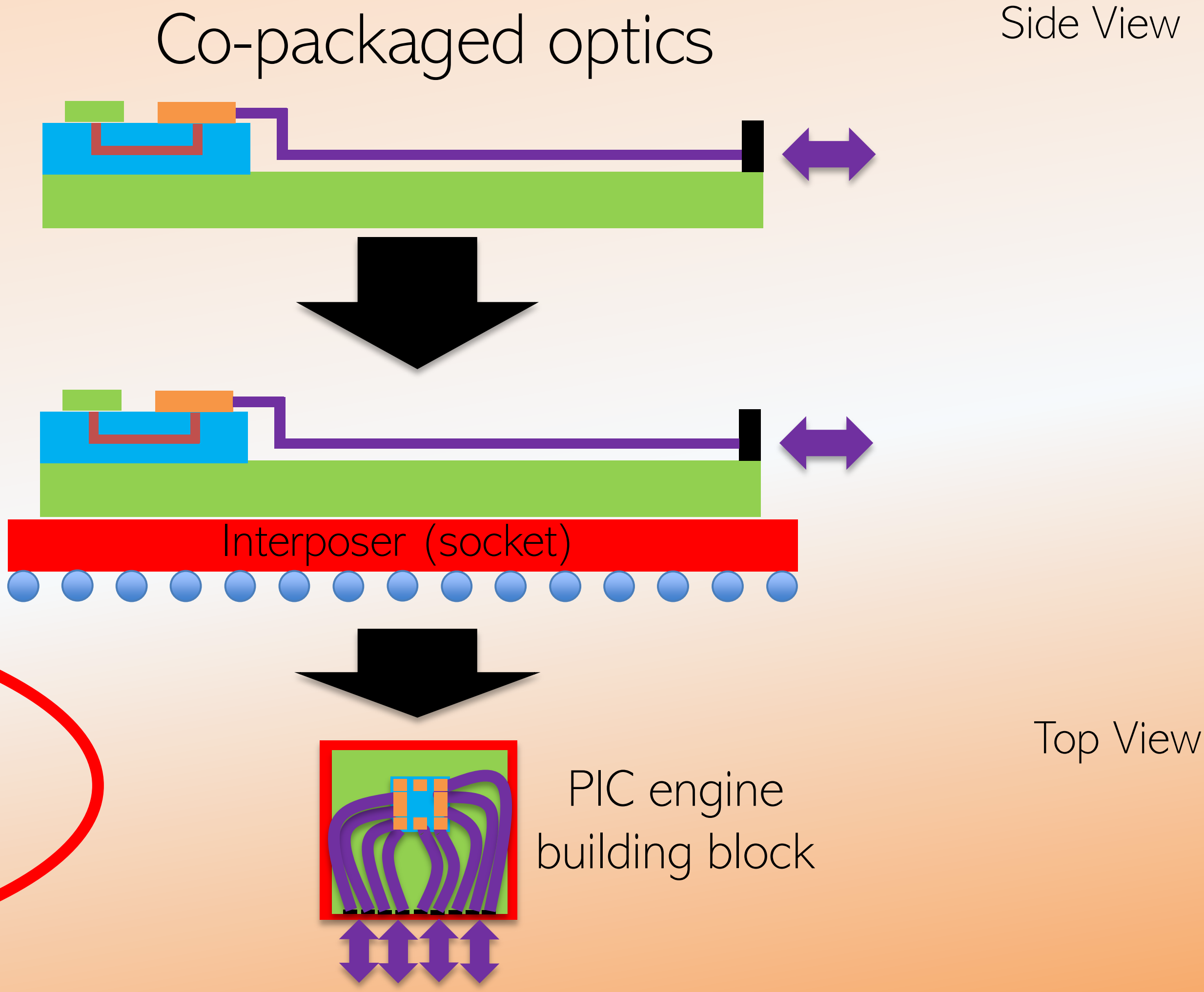
- Current switches support 12.8Tbps I/O
  - 16nm CMOS (e.g. Broadcom Tomahawk 3 switch)
  - Pluggable modules (potential to scale to 25Tbps)
- Next generation needs up to 400Tbps I/O capacity
  - 1kW at 10pJ/bit → huge heat source !!
  - I/O expensive, power prohibitive
- Customers want
  - 100Tbps, scaling to 400Tbps I/O capacity
  - <5pJ/bit (to keep power in check)
  - Smaller size → miniaturization
  - Perhaps a different solution?



Co-packaging optics enables high traffic throughput

Source: Lightwave Logic (LWLG), OFC2019

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Co-packaging open questions

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- Co-packaging now viewed as inevitable
  - Not clear how to get there – higher levels of integration
  - Ecosystem will change significantly as technology will change
  - From OFC2019, "the future has never been as fuzzy"
- Route to 400Tbps using 800/1600Gbps
  - Not an extrapolation; not just an extension of what has been done before
- *Co-packaging is different…*

New challenges bring *new opportunities* for PICs

Source: Lightwave Logic (LWLG), OFC2019

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Route to multi-100Tbps PCP-MCM

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Polymer Co-Packaged Multi-Chip Module

Use of polymer (organic PCB) technology throughout

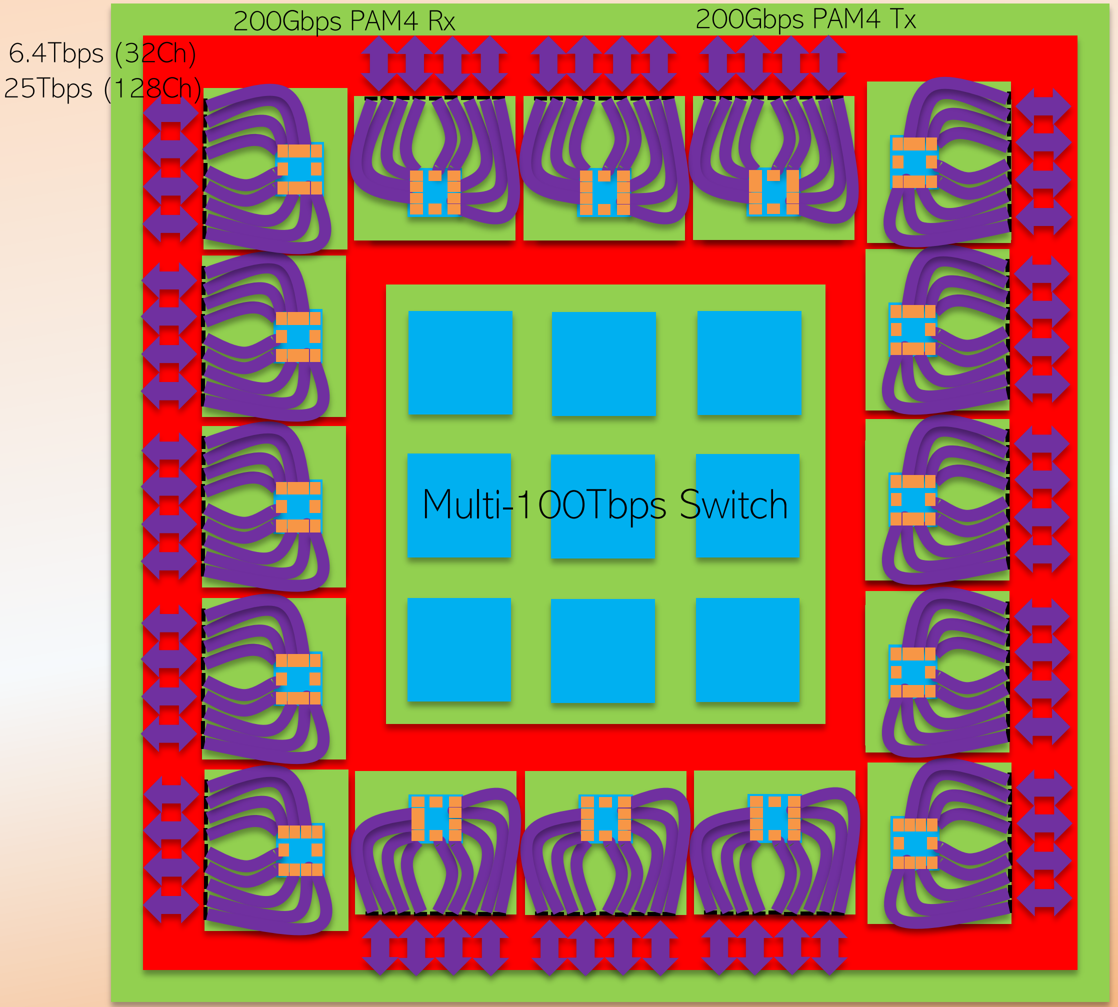
Passive waveguides, coupling, boards

Active modulators

- Polymer passives
  - Waveguide interface
- Polymer 80GHz modulators
  - 100Gbps NRZ or
  - 200Gbps PAM4

- 32 channels x 200 Gbps = 6.4 Tbps/ PIC engine
  X 16 engines = 102.4 Tbps

- 128 channels x 200 Gbps
  X 16 engines = 400 Tbps



Top View

Polymer PIC engine as building block for 400Tbps solutions

Direct drive CMOS → saves power

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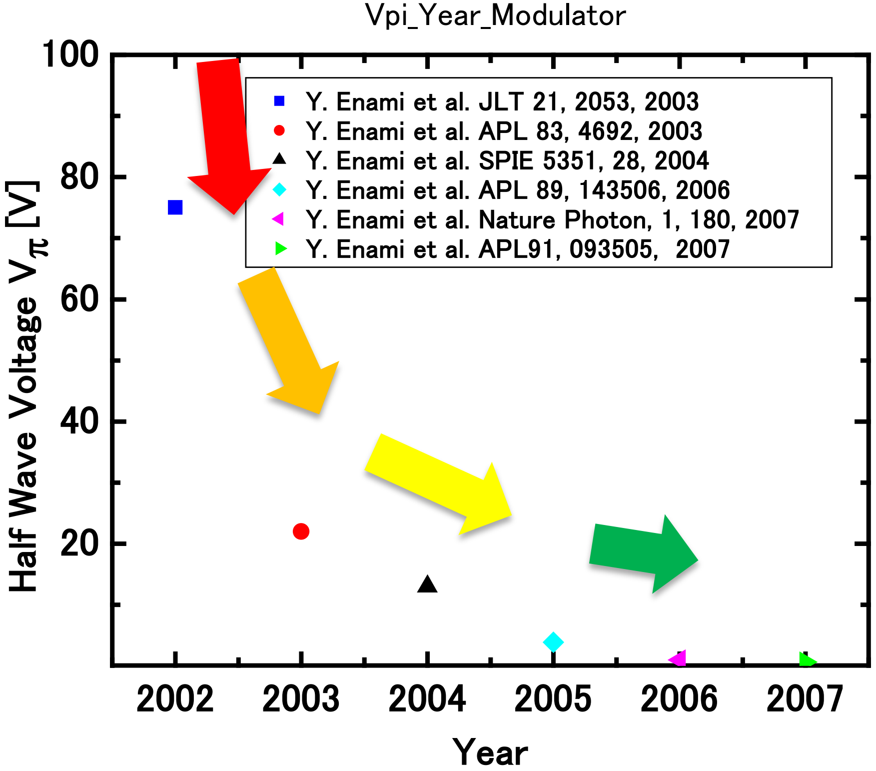
- Lower voltage operation save power
- Also means the modulators can be driven directly from a CMOS chip
- No driver chips necessary
  - Saves even more power
  - Also saves $$$



Source: Lightwave Logic (LWLG); Yasufumi Enami (University of Kochi, Japan; University of Arizona)

Polymer modulators are *driverless, low power, and save $$$*

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Lower cost…

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Simple, low cost fabrication

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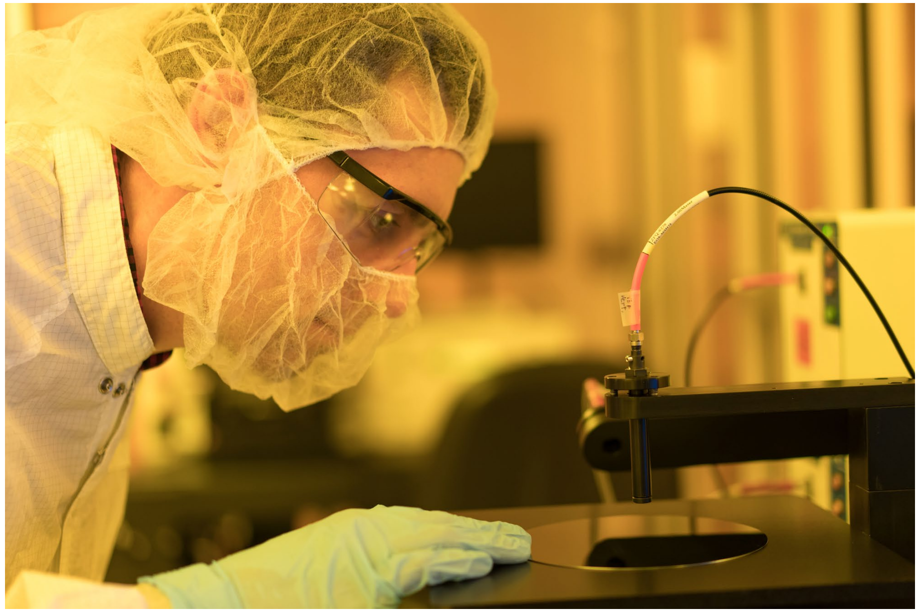
Fabrication equipment and process is simple

- No exotic equipment needed
  - Standard photolithography to pattern
  - Wafer scalability
  - Minimize cycle time



Lower costs can be enabled through simplicity in fabs

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Integrate platforms → Hybrid solutions

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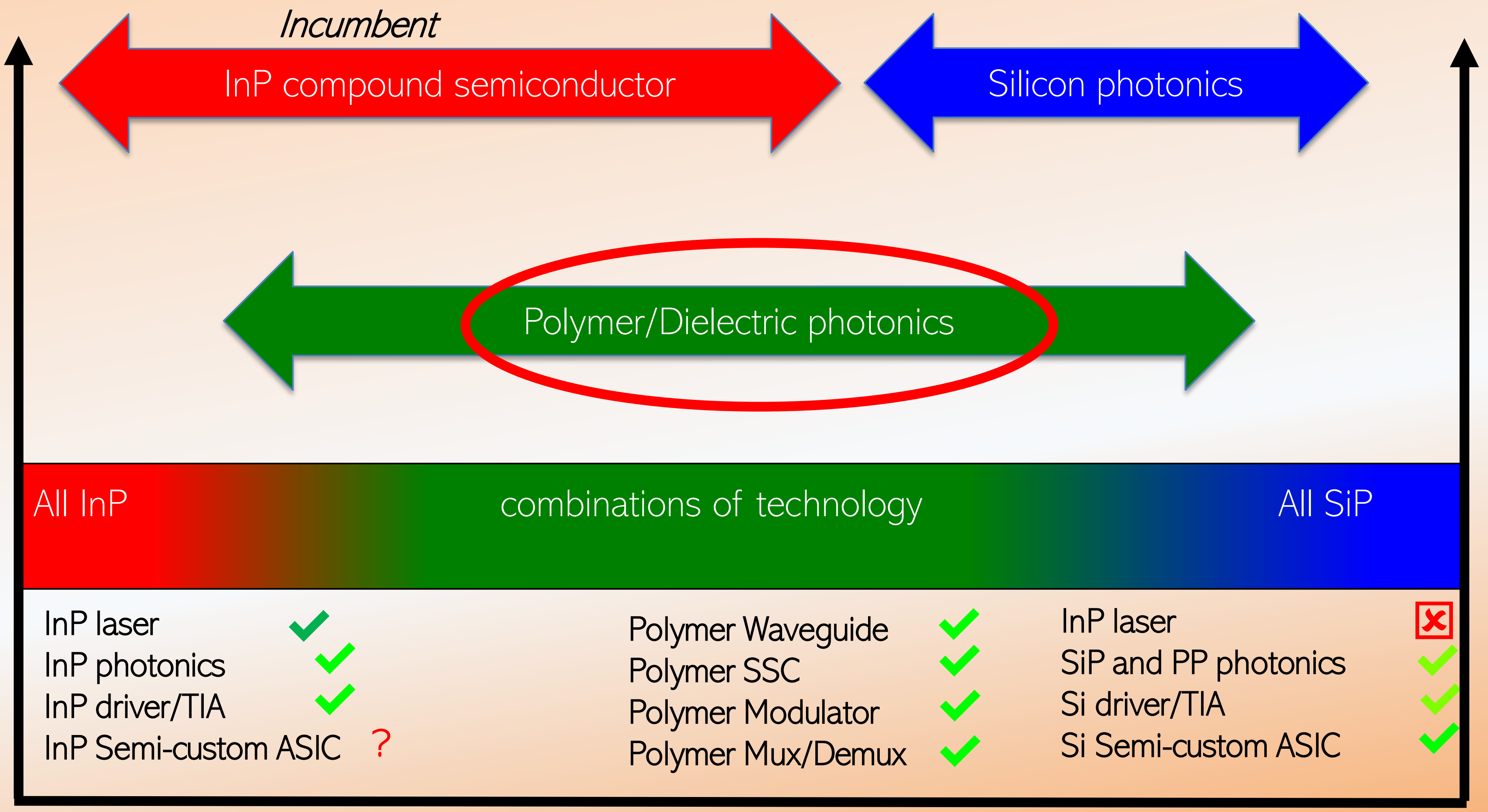

Lower costs enabled through integration of hybrid technologies

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Lower cost via protocol planning

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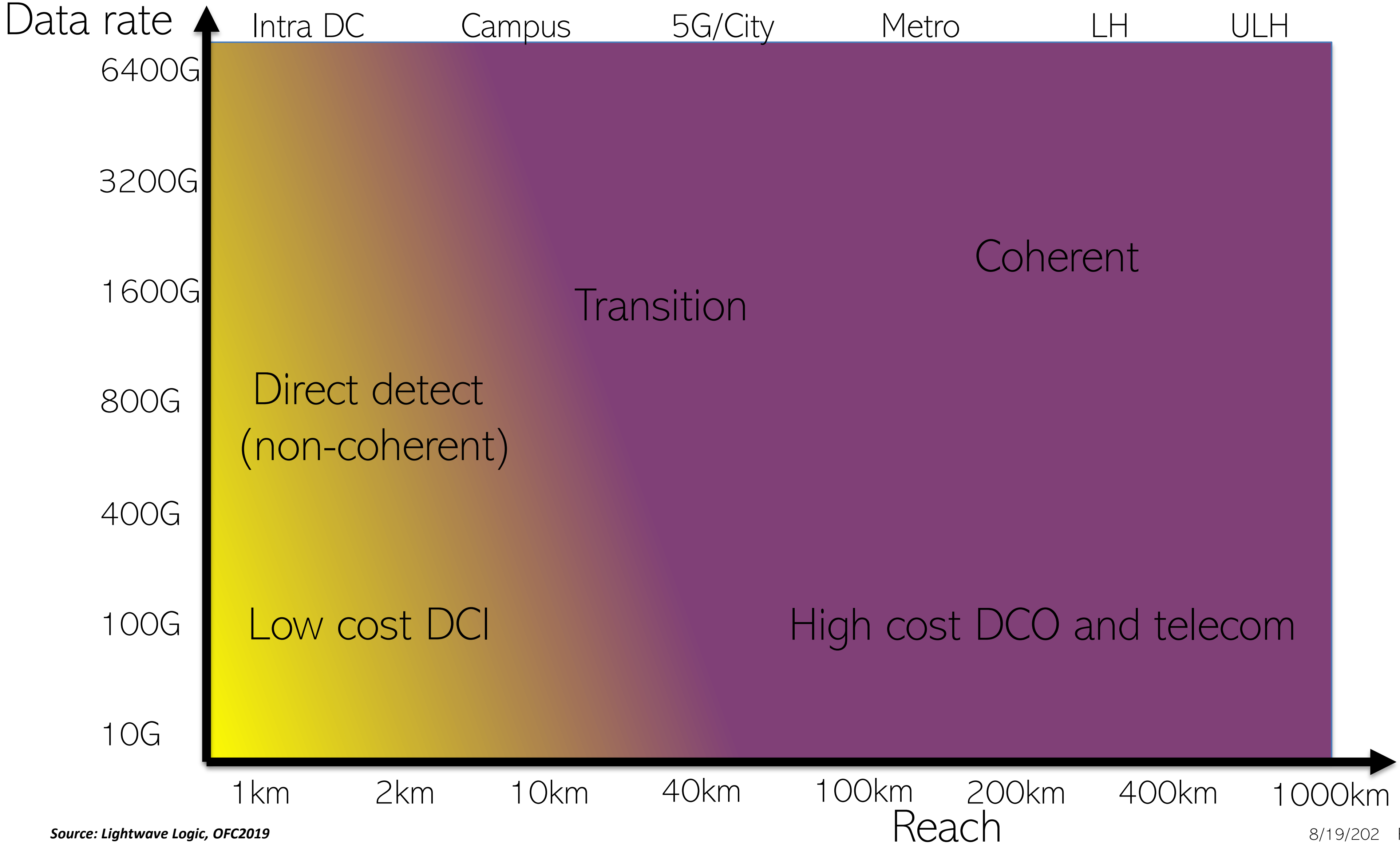

Source: Lightwave Logic, OFC2019

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Direct detect vs coherent

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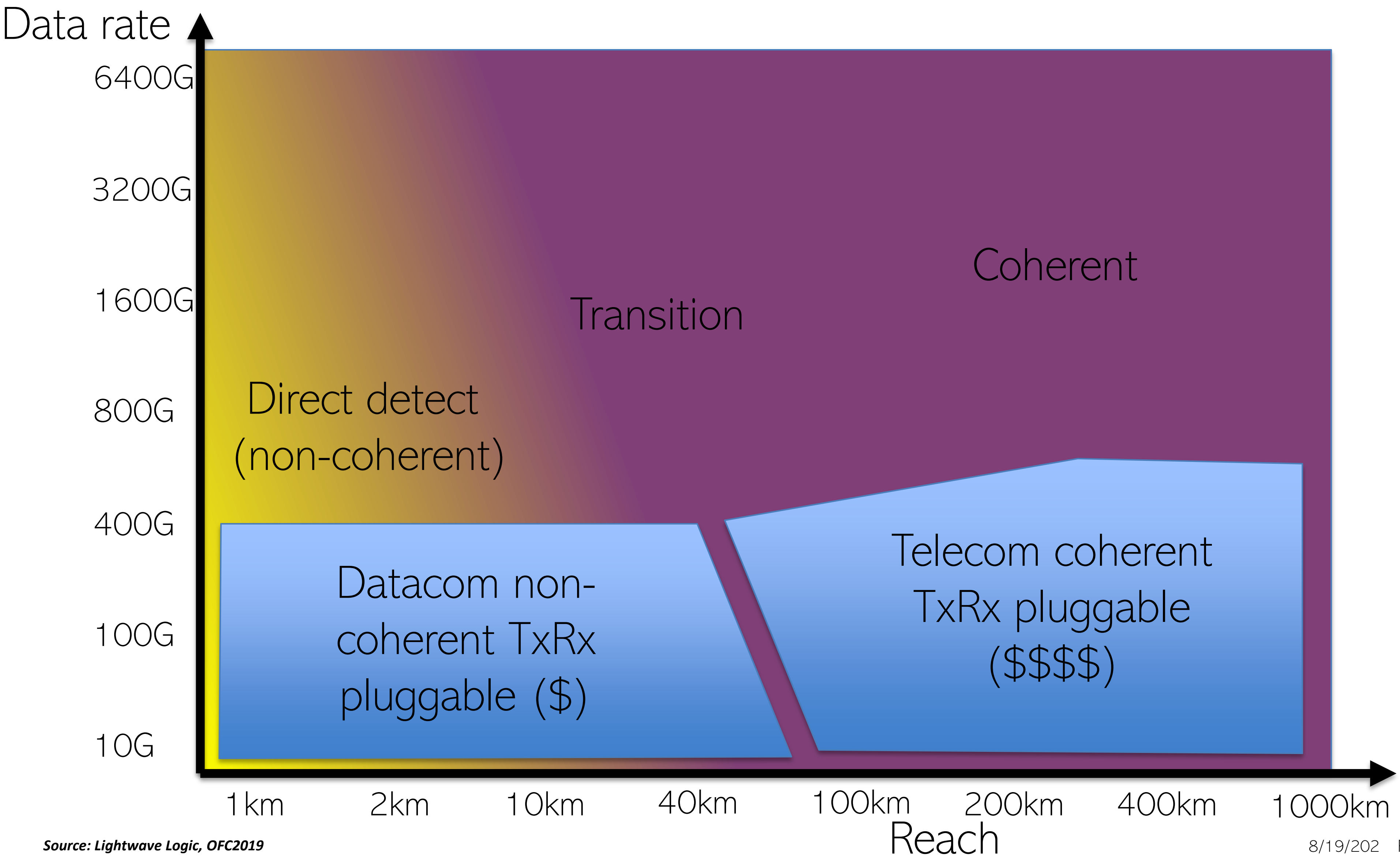

Source: Lightwave Logic, OFC2019

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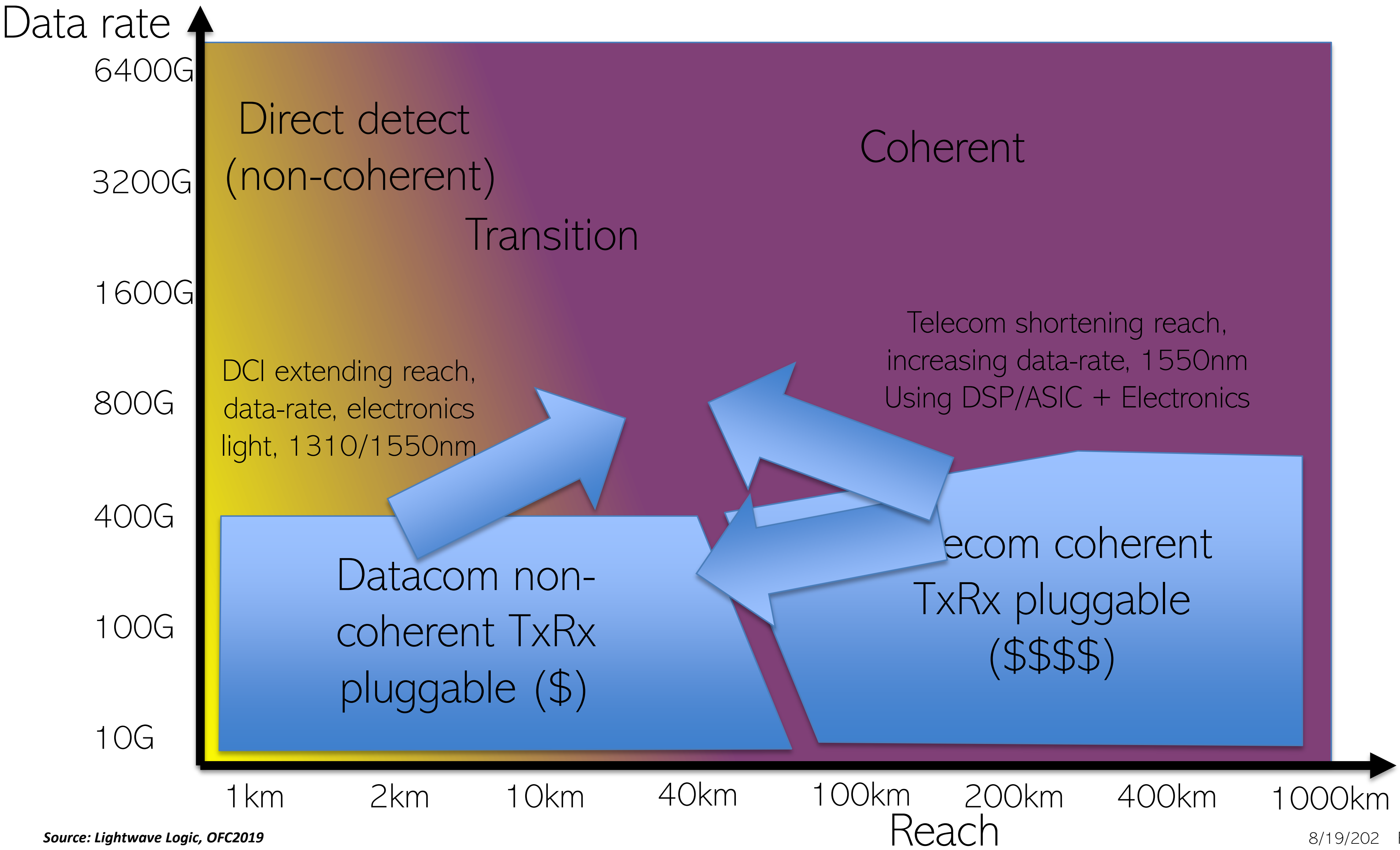
Merging fronts…cost, power and…

LIGHTWAVE LOGIC



Source: Lightwave Logic, OFC2019

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Battleground for cost, power, and speed

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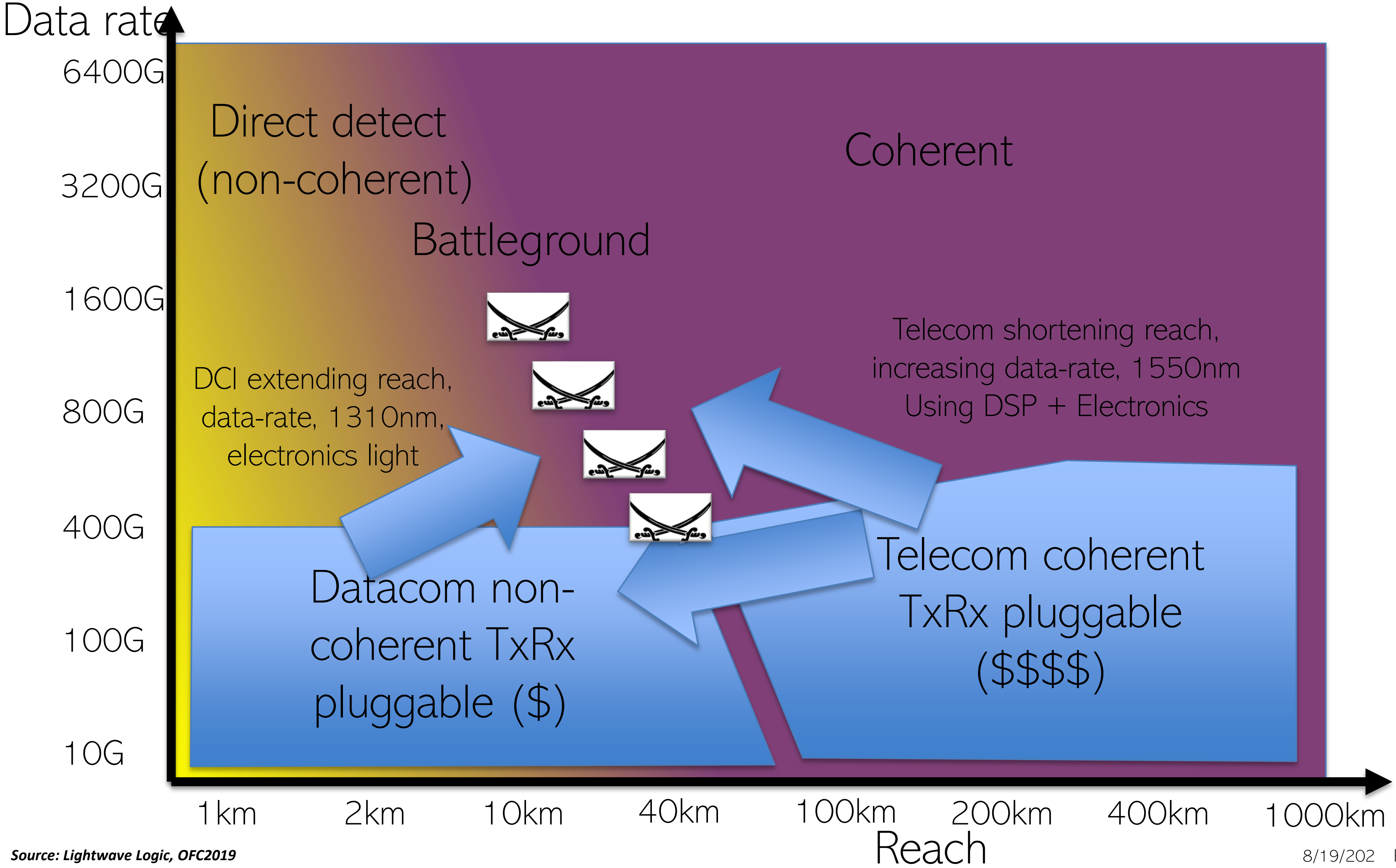

Source: Lightwave Logic, OFC2019

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OTCQB: LWLG

Robust…

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PIC opportunities expand but need robustness

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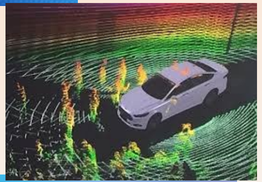
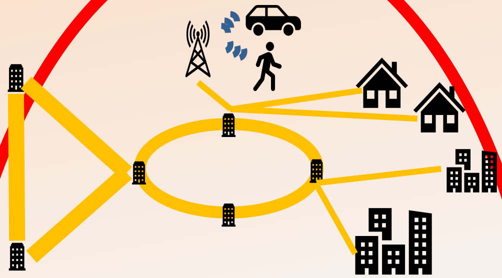
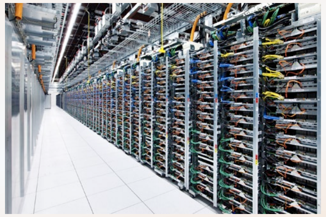
- 5G systems
- RF over fiber
- Automotive (LIDAR)
- Optical sensing
- Bio-photonic sensing
- Medical
- Instrumentation
- Others…



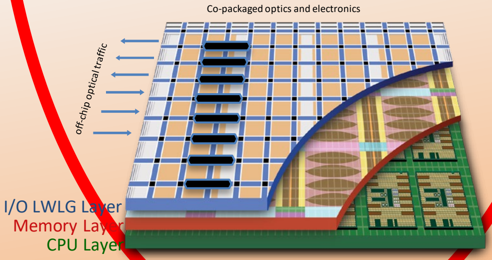




Telecommunications



Data communications



High performance computing

Maturity (and robustness) in Fiber Comm enables other markets

Source: Mitsubishi Electric, Luxtera, IBM, Google

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PIC semiconductor robustness/rel

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- Telecommunications always relied on Telcordia testing (GR-468 etc)
  - 10-20 year lifetime, low FIT rates, accelerated testing
- Datacommunications (datacenters) looked at simplifying R&QA to reduce cost
  - Recent datacenter requirements proposed 3yr fork-lift equipment changes, and reduced R&QA expectations
  - Today's datacenter folks are now looking to re-establish high reliability testing to reduce failure rates from 1000s of photonics equipment
- Net net → R&QA is still critical and needs to be taken very seriously
  - Next generation PICs must aim towards Telcordia requirements

R&QA needs to be aimed between datacom and telecom today

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Electro-optic polymers meet the grade

LIGHTWAVE LOGIC

- Standard Telcordia CR-468 reliability testing
- Robust materials

Test Item	Test Description	Specification: Method or Conditions	Sample Data	Passed Y/N
HTOL	High temperature operation life time test	Telcordia GR_468_COREi02 3.3.3.1; 2000 hrs at power, driver, bias and Ta = 85ºC	11	Y
Low Temperature Storage	Storage only in low temperature	Telcordia GR_468_COREi02 3.3.2.1 -40ºC, 72 Hour	11	Y
Mechanical Shock	Apply mechanical shocks to device	Telcordia GR_468_COREi02 3.3.1.1; mil-std-883 Method 2002.3	7	Y
Vibration	Apply vibration to devices	GR_468_COREi02 3.3.1.1; mil-std-883 Method 2007.2.	6	Y
Thermal Shock	Sudden exposure to extreme changes in temperature	Telcordia GR_468_COREi02 3.3.1.2; mil-std-883 Method 1011.9.	11	Y
Fiber Twist	Twist fiber pigtail	Telcordia GR_468_COREi02 3.3.1.3.1; FOTP 36.	8	Y
Fiber Side Pull	Pull fiber pigtail	Telcordia GR_468_COREi02 3.3.1.3.2; GR-326-CORE 4.4.3.5.	8	Y
Cable Retention	Apply force to the cable	Telcordia GR_468_COREi02 3.3.1.3.3; FOTP 6.	11	Y

Source: Lightwave Logic (LWLG), BrPhotonics

Battery of testing completed

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We must deliver radical innovation

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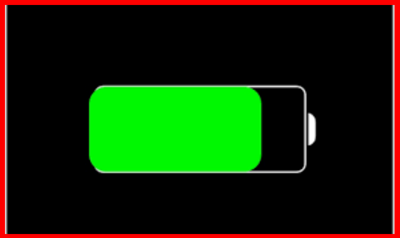
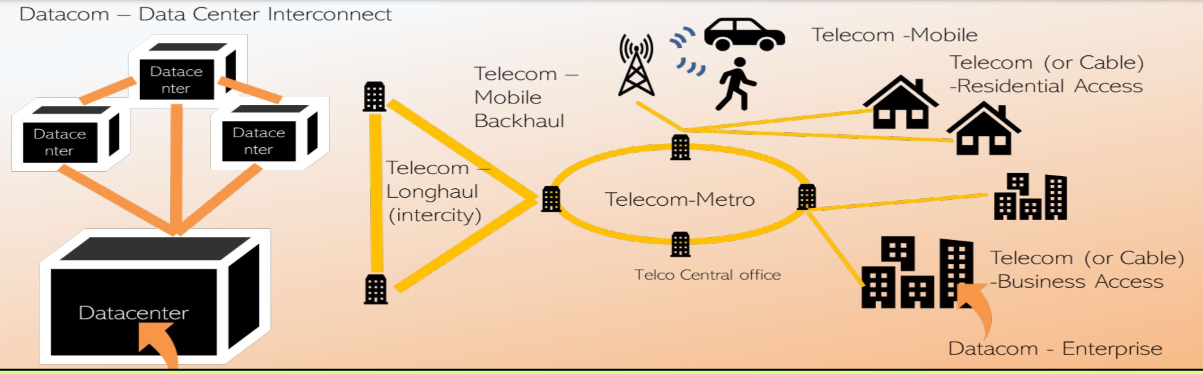
Faster devices (100GHz+)	Lower Power (Low voltage)	Lower cost (Easy fab)	Robust (Stable)
			



To enable faster, lower power, lower cost internet…

Source: Lightwave Logic (LWLG)

 © Lightwave Logic, Inc.

Electro-optic polymer example

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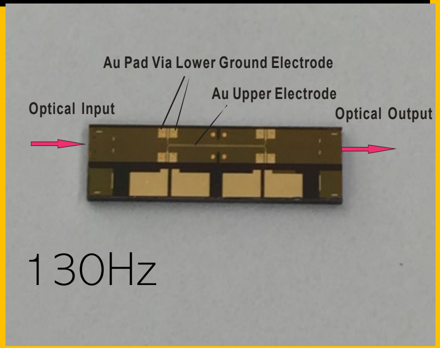
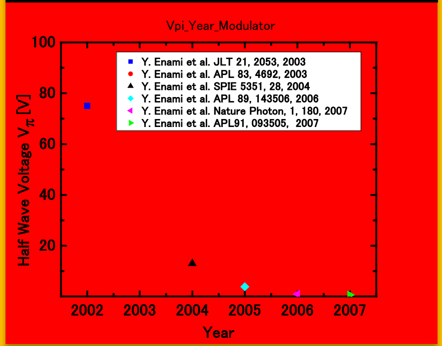
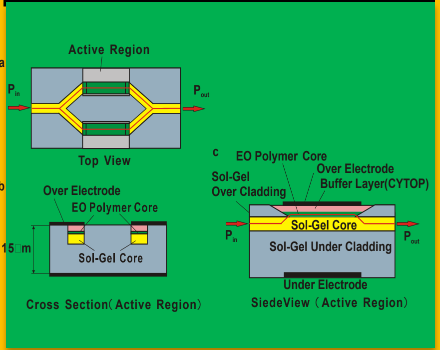
Faster devices
(100GHz+)



Lower Power
(Low voltage)



Low cost
(Easy fab)



Robust
(Stable)

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They enable *radical innovation…*

Source: Lightwave Logic (LWLG)

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OTCQB: LWLG

Roadmap update

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Fastest by Design

Roadmaps: What did we predict in 2016?

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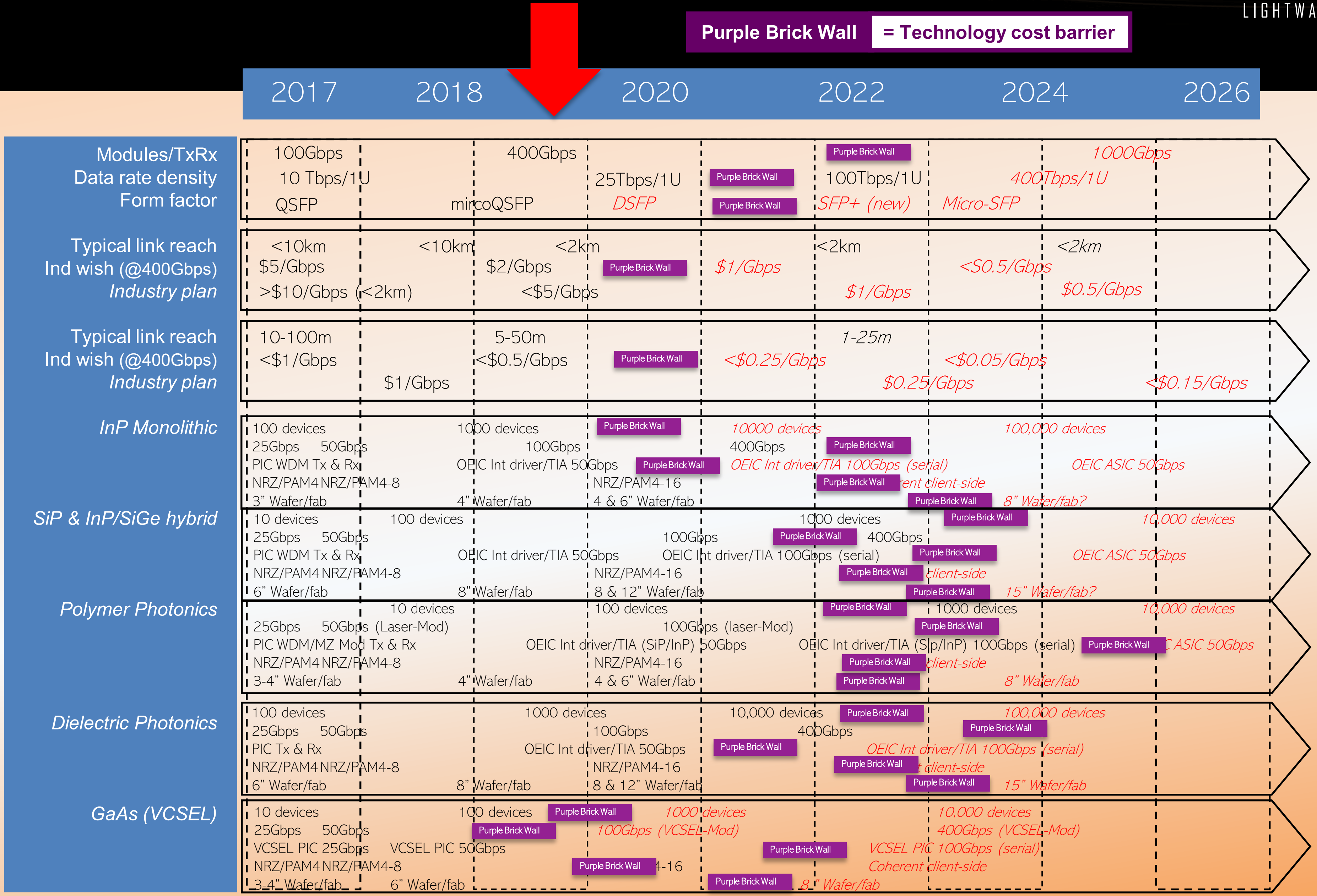
Purple Brick Wall **= Technology cost barrier**

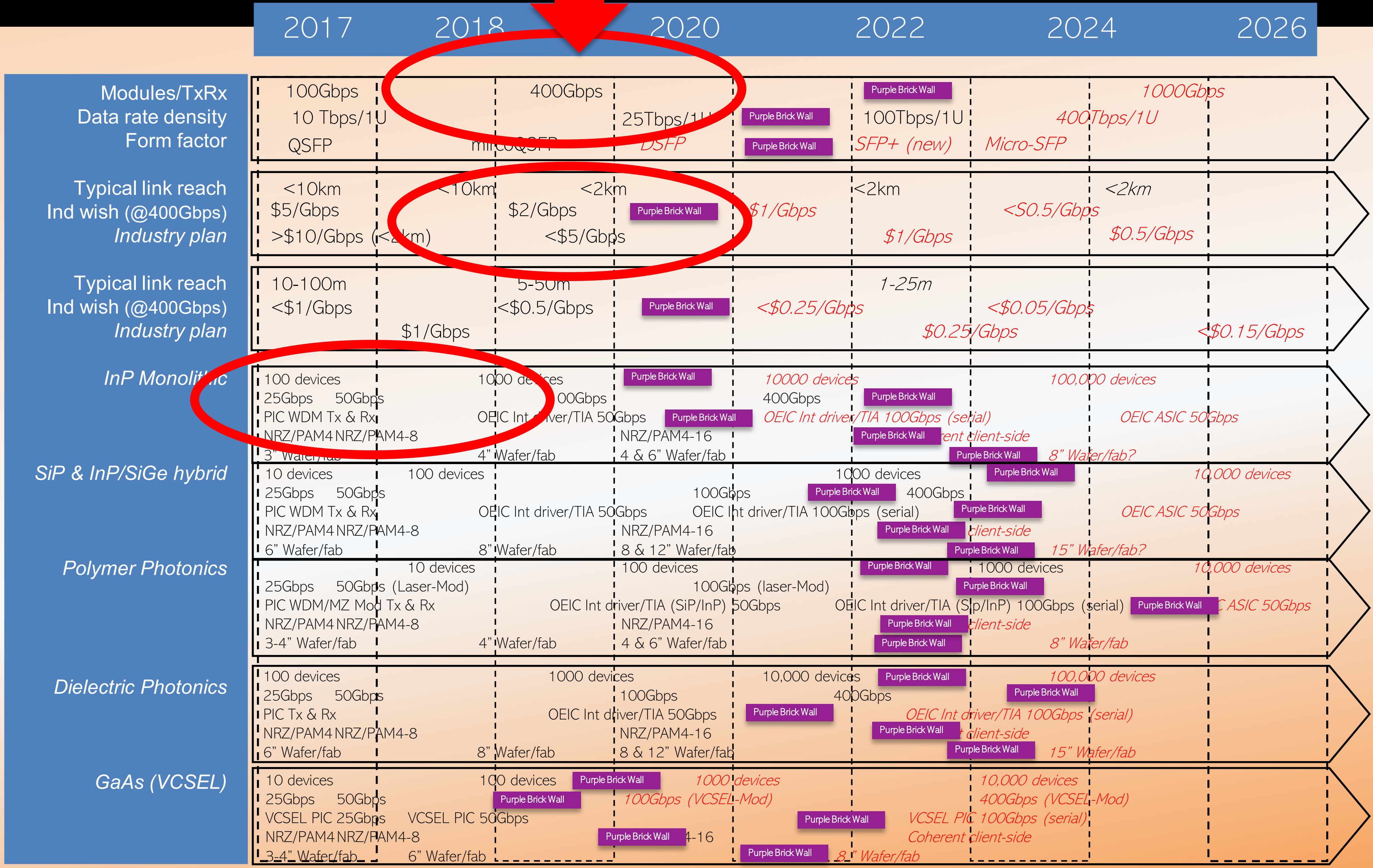


Slanted Red Font: Major industry efforts are required for commercialization

Source: Lightwave Logic

Actually pretty good → TxRx 400Gbps, <$5/Gbps, 50Gbps+ devices

Purple Brick Wall = Technology cost barrier



Slanted Red Font: Major industry efforts are required for commercialization

Source: Lightwave Logic

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New draft in 2019 → Where are we going?

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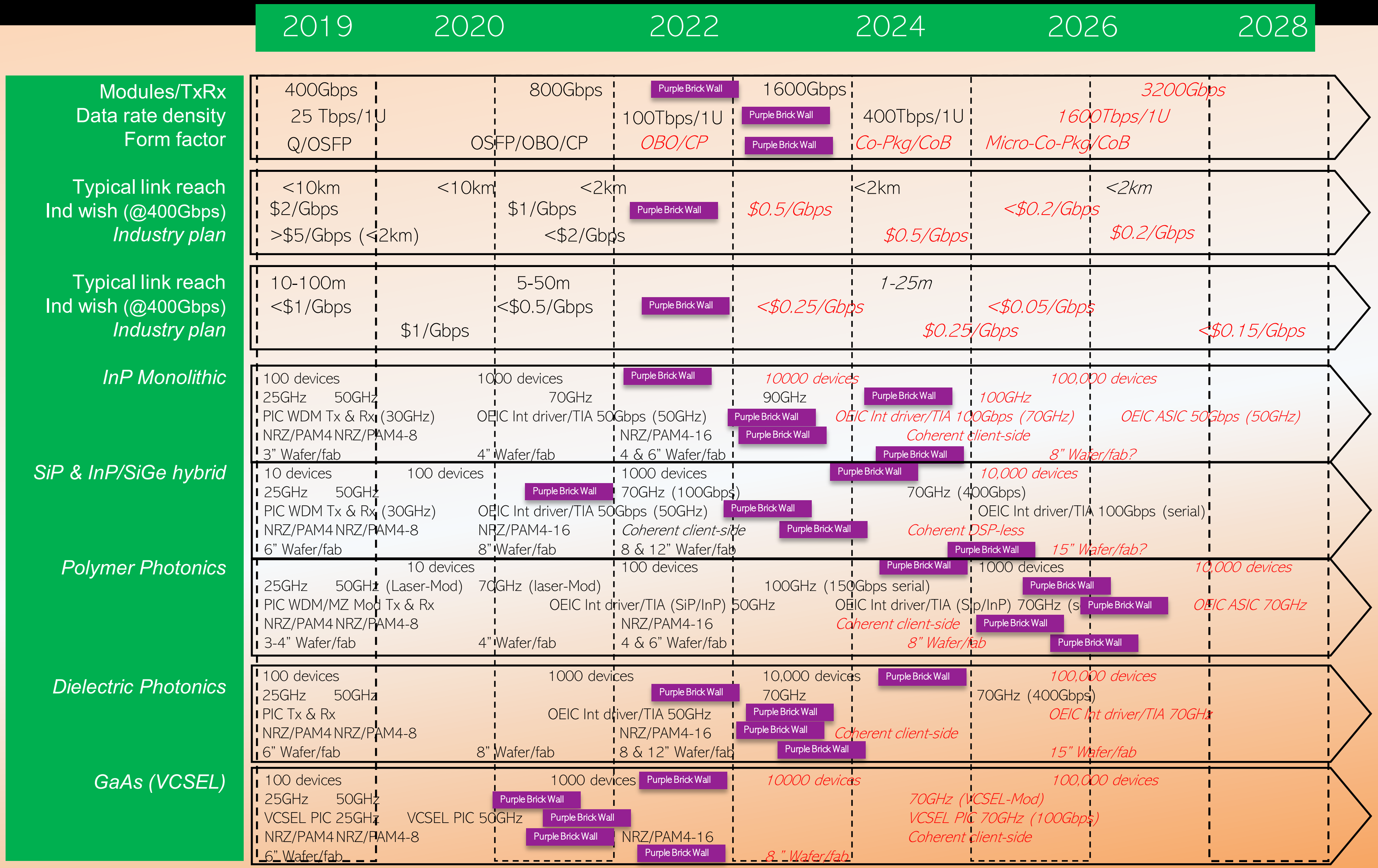
Purple Brick Wall = Technology cost barrier



Slanted Red Font: Major industry efforts are required for commercialization

Source: Lightwave Logic

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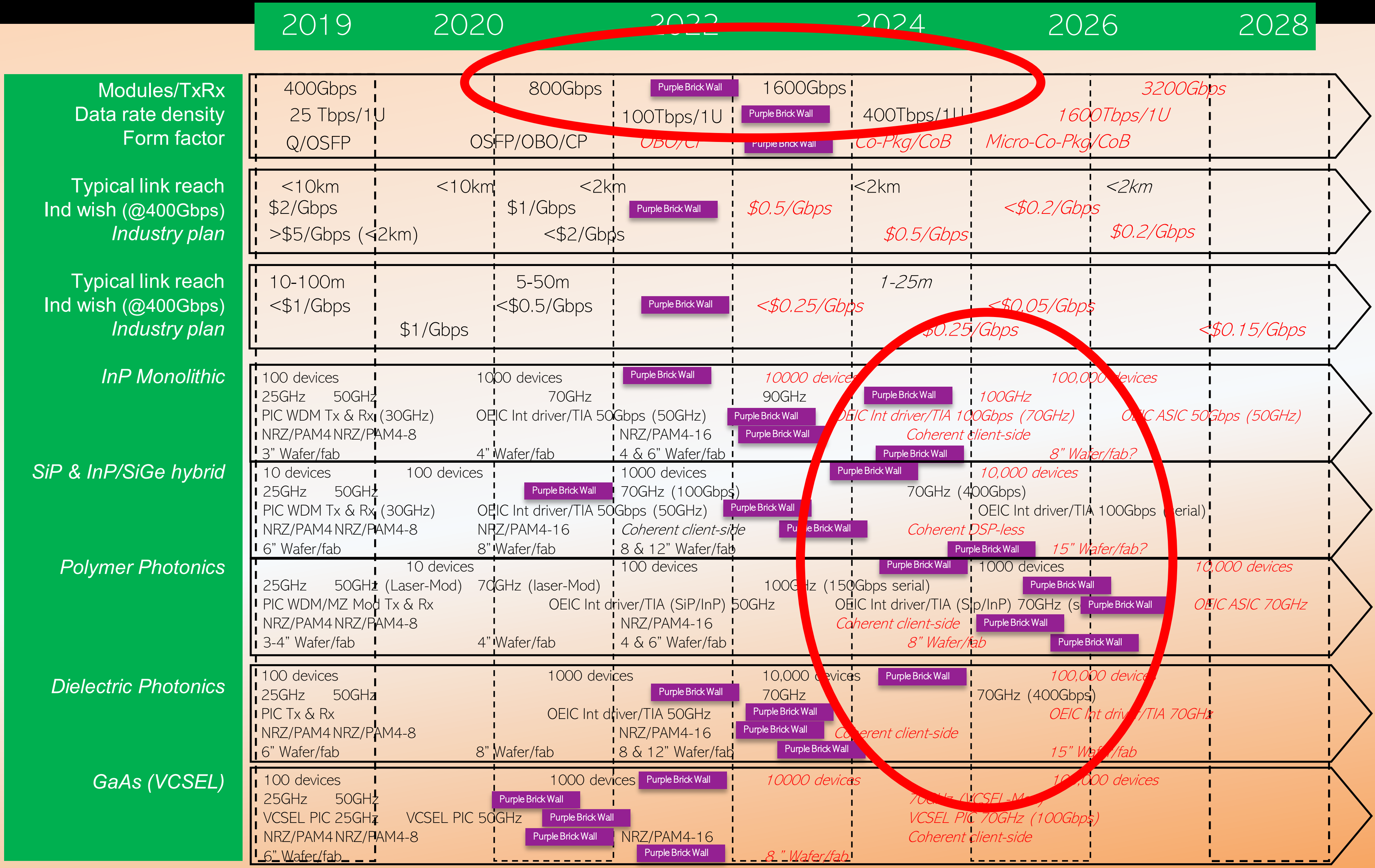
800 and 1600Gbps; very high bandwidth 70GHz, co-packaging, low power, hybrid integration, low $/Gbps



Slanted Red Font: Major industry efforts are required for commercialization

Source: Lightwave Logic

Call to action…

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- Roadmap slides convey clear messages
  - Challenges to move data faster, more efficiently are not slowing down
  - PIC platforms are critical for size, weight, and power
  - Innovation is desperately needed amongst our current technological platforms
- How are we going to make this happen?
  - We support the roadmaps and use roadmaps to generate investment (foundries, clusters, centers etc)

Learn to shout at the political level for photonics…

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OTCQB: LWLG

Summary

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Fastest by Design

Summary

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- Internet still growing quickly driven by video ✓
  - Internet key application, others emerging (bio, automotive, medical…)
  - Strong $B markets in fiber communications with forecasted growth
- Integrated photonics continue to be strong ✓
  - PICs will mature over the decade in fiber communications
  - Trend to co-packaging, low power, high bandwidth, low cost coherent
  - Hybrid PICs will become common-place to increase specifications
- We see our polymers solving customer headaches ✓
  - Our polymers add speed dimension, low power, cost effective to internet
- Call to action? 
  - Utilize our roadmaps to energize political levels internationally ✓
  - Let's make the roadmaps our tool for success…

Let's make the next decade a photonic one…*radical innovation*

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LIGHTWAVE LOGIC™

OTCQB: LWLG

Thank you

Symbol OTCQB: LWLG

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